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Microwave Attenuation and Brightness Temperature Due to the Gaseous Atmosphere

A Comparison of JPL and CCIR Values

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ABSTRACT

Attenuation by the gaseous atmosphere and brightness temperature (sky noise temperature in a given direction) due to emission from the gaseous atmosphere are related and should be derived from a common radiative transfer program in order to assure internal consistency. The Jet Propulsion Laboratory has developed a sophisticated but flexible radiative-transfer program, which was used to produce the gaseous attenuation and brightness temperature curves found in two basic reports of the 1978 Proceedings of the CCIR [Comité Consultatif International des Radiocommunications (International Radio Consultative Committee)]. In this report, a comparison of each of these curves is made and a new set is derived from the JPL program, covering a frequency range of 1 to 340 GHz.

PREFACE

In the fall of 1979 the Jet Propulsion Laboratory (JPL), with support from NASA's Office of Space and Terrestrial Applications, initiated a feasibility study to see whether it was desirable and possible to develop from a single master computer program the basic CCIR [Comite Consultatif International des Radiocommunications (International Radio Consultative Committee)] information on attenuation and sky noise temperature due to the earth's atmosphere. It was concluded from internal consistency checks that the need existed. A search for an appropriate computer code uncovered an excellent one at JPL for use with the gaseous atmosphere (Waters, 1976). It was further concluded that inclusion of rain effects was premature and should be deferred for the time being.

Informal submissions were made by JPL to the Interim Meeting of Study Group 5 (June 1980) and most of the inconsistencies in CCIR Report 719 (CCIR, 1978a) were resolved at the Interim Meeting. While inconsistencies in the CCIR brightness-temperature curves of Report 720 (CCIR, 1978b) were pointed out at that time, new curves were not yet available. These have now been submitted, in the form of U.S. Study Group 5 documents, through regular CCIR channels to the final meeting of CCIR Study Group 5 (Geneva August 24-September 11, 1981), along with the gaseous attenuation modifications. When endorsed by the forthcoming CCIR XVth Plenary Assembly, in 1982, the new texts (CCIR, 1982a, b.) will officially replace the existing Reports 719 and 720.

Much of the substance of this text was presented in a paper to URSI [Union Radio Scientifique Internationale (International Union of Radio Science)] Commission F at the National Radio Science Meeting January 14, 1981 in Boulder, Colorado. At that time other organizations were invited to submit their programs for comparison. Dr. Hans Liebe of the Institute for Telecommunication Sciences, National Telecommunications and Information Administration, subsequently offered his comprehensive program on attenuation and dispersion by atmospheric gases (Liebe, 1981). A comparison of his results for

specific attenuation due to the gaseous atmosphere with those of the JPL program and the CCIR-proposed revised curves indicates excellent agreement.

CONTENTS

1	INTRODUCTION -----	1
1.1	PURPOSE -----	1
1.2	BACKGROUND -----	1
1.2.1	The Atmosphere -----	1
1.2.2	Gaseous Attenuation -----	4
1.2.3	CCIR Gaseous Attenuation Curves -----	5
1.2.4	Brightness Temperature -----	6
2	INTERNAL CONSISTENCY -----	9
2.1	THE SCALE HEIGHT TEST -----	9
2.2	BRIGHTNESS TEMPERATURE--ABSORPTION COMPARISON -----	10
3	COMPARISON OF CCIR AND JPL VALUES -----	11
3.1	THE JPL PROGRAM -----	11
3.2	COMPARISON OF GASEOUS ABSORPTION -----	11
3.3	COMPARISON OF BRIGHTNESS TEMPERATURE -----	12
4	CURVE SETS -----	13
4.1	JPL CLEAR-AIR ABSORPTION -----	13
4.2	JPL BRIGHTNESS TEMPERATURE -----	14
5	CONCLUSION -----	15
	REFERENCES -----	17

Figures

1	Atmospheric reduced-equivalent thickness above indicated altitude -----	21
2	Variation of optical air mass, with elevation angle, for a ray traversing the atmosphere -----	22

CONTENTS (Continued)

Figures

3	Specific attenuation by atmospheric gases -----	23
4	Total one-way zenith attenuation through the atmosphere -----	24
5	Theoretical one-way attenuation from specified height to the top of the atmosphere -----	25
6	Sky noise temperature (clear air) for surface pressure of 1 atmosphere and temperature of 20°C and a surface water-vapor concentration of 3 g/m ³ -----	26
7	Sky noise temperature (clear air) for surface pressure of 1 atmosphere and temperature of 20°C and a surface water-vapor concentration of 10 g/m ³ -----	27
8	Sky noise temperature (clear air) for surface pressure of 1 atmosphere and temperature of 20°C and a surface water-vapor concentration of 17 g/m ³ -----	28
9	Apparent scale height for oxygen absorption in the atmosphere -----	29
10	Comparison of apparent and true atmospheric reduced-equivalent thickness from JPL radiative-transfer program for quotient -----	30
11	Zenith brightness temperature for 3, 10, and 17 g/m ³ water vapor -----	31
12	Comparison of specific attenuation by atmospheric gases -----	32
13	Comparison of zenith attenuation by the atmosphere (clear air) -----	33
14	Comparison of zenith attenuation for various specified heights -----	34

CONTENTS (Continued)

Figures

15	Comparison of CCIR and JPL brightness temperatures for an arid atmosphere -----	35
16	Comparison of CCIR and JPL brightness temperatures for an average atmosphere -----	36
17	Comparison of CCIR and JPL brightness temperatures for a moist atmosphere -----	37
18	Specific attenuation (absorption) from the JPL radiative-transfer program for 290 K, 7.5 g/m ³ water vapor and dry (O ₂) atmospheres -----	38
19	Total one-way zenith attenuation from the JPL radiative-transfer program for: the 1976 U.S. standard model atmosphere, 7.5 g/m ³ water vapor (2-km scale height) and O ₂ atmospheres -----	39
20	Zenith attenuation as a function of station elevation: 4-km height increments from 0 to 16 km -----	40
21	Zenith brightness temperature for 0, 3, 10, 17 g/m ³ of water vapor (2-km scale height) added to the 1976 U.S. standard model atmosphere -----	41
22	Brightness temperature for 7.5 g/m ³ water vapor (2-km scale height) added to the 1976 U.S. standard model atmosphere -----	42
23	Brightness temperature for 3 g/m ³ water vapor (scale height 2 km) added to the 1976 U.S. standard model atmosphere, 1 to 340 GHz -----	43

CONTENTS (Continued)

Figures

24	Brightness temperature for 7.5 g/m^3 water vapor (scale height 2 km) added to the 1976 U.S. standard model atmosphere, 1 to 340 GHz -----	44
25	Brightness temperature for 17 g/m^3 water vapor (scale height 2 km) added to tropical model atmosphere (15°N) (Valley, 1965); 1 to 340 GHz -----	45

Tables

1	Atmospheric Model Used in All Calculations With the JPL Radiative-Transfer Program Except for Fig. 25 -----	19
2	Tropical Atmosphere Model (15°N Latitude) -----	20

SECTION 1

INTRODUCTION

1.1 PURPOSE

It is frequently difficult to trace the origins of the propagation and noise curves of the CCIR [Comité Consultatif International des Radiocommunications (International Radio Consultative Committee)]. These curves provide the technical basis of the discussions that lead to international treaties in radio frequency allocations. This report compares the present CCIR standard propagation and noise curves pertinent to earth-space telecommunications with those derived from a sophisticated, up-to-date radiative transfer program (Waters 1976), in an attempt to assess the adequacy of the present set and if necessary offer some possible alternative curves.

1.2 BACKGROUND

1.2.1 The Atmosphere

The earth's dry atmosphere consists of oxygen (O_2), 20.946% by volume, nitrogen (N_2), 78.084% by volume, and argon (A), 0.934% by volume. These three total 99.964% and, along with 27 parts per million of trace gases, are well mixed to a height of nearly 80 km, where the dissociation of molecular to atomic oxygen begins to affect these figures. Carbon dioxide (CO_2) accounts for about 333 parts per million and is also well-mixed in the atmosphere, but it is increasing at about 0.7 parts per million per year (Battan, 1979). This brings the total to 100%.

The principal variable component of the atmosphere is water vapor (H_2O). The saturation vapor pressure is a very strong function of temperature. For example, the saturation partial pressure of water vapor (over water) is 6.107 mb at $0^\circ C$, 12.27 mb at $10^\circ C$, 23.37 mb at $20^\circ C$, 42.43 mb at $30^\circ C$, and 73.78 mb at $40^\circ C$. Relative to the U.S. standard model atmosphere at sea level ($15^\circ C$,

1013.25 mb), we see that water vapor at 100% relative humidity constitutes only about 1.7% by volume of the atmosphere.

The height profile of pressure and density of the static dry atmosphere can be described quite adequately by two fundamental equations. The hydrostatic equation describes the pressure profile, with height. In differential form it is:

$$dp = -\rho g dh \quad (1)$$

where p is pressure, ρ the atmospheric density, g the acceleration of gravity, and h the altitude.

The relationship of pressure and temperature is given by the perfect-gas law, which may be written in the form

$$p = nkT \quad (2)$$

where n is the particle density ($2.5473 \times 10^{25} \text{ m}^{-3}$ at 15°C and 1013.25 mb), k is Boltzmann's constant ($1.3804 \times 10^{-23} \text{ J/K}$), and T the temperature in kelvins. Combining (1) and (2),

$$\frac{dp}{p} = -\frac{g\rho}{nkT} dh = -\frac{dh}{H} \quad (3)$$

where the scale height $H = \frac{kT}{\bar{m}g}$, and $\bar{m} = \rho/n$ is the average particle mass.

The significance of scale height may be understood by integrating (3):

$$p = p_0 \exp \left[-\int_0^h \frac{mg}{kT} dh \right] \quad (4)$$

which, if the variation in g and T is ignored, yields

$$\frac{P}{P_0} = \frac{n}{n_0} = \exp (-h/H) \quad (5)$$

illustrating that the pressure or particle density decreases by a factor of e in one scale height (about 8 km at the earth's surface), assuming isothermal conditions. Further, by integrating (5):

$$n = n_0 \int_0^\infty \exp \left(-\frac{h}{H} \right) dh = n_0 H \quad (6)$$

which can be interpreted to mean that the total number of particles in the atmosphere may be obtained by multiplying the surface particle density n_0 by the scale height H . Hence, the scale height is frequently equated to the equivalent thickness of the atmosphere.

The "atmospheric reduced-equivalent thickness" (Gast, 1965), or, simply, the "reduced thickness", is a similar concept to scale height, interpreted as equivalent thickness as in (6). Atmospheric reduced-equivalent thickness is used to gauge the air mass, which must be traversed by an optical ray transiting the atmosphere at its zenith. It is defined as the equivalent thickness of an isothermal atmosphere at 0°C , or 15°C and 1013.25 mb surface pressure. For example, at sea level the reduced thickness at 0°C and 1 atm is 8.0 km while at 15°C and 1 atm it is 8.4 km. As one goes up in height the mass above the observer decreases, as shown in Fig. 1.

The optical air mass, m , is a companion concept that relates an oblique path to the zenith path. Thus

$$m = \frac{\ell_m}{\ell_z} \cong \sec \delta \text{ for } \delta < 75^\circ \quad (1\% \text{ error at } \delta = 75^\circ)$$

where ℓ_m is the reduced-equivalent path at an oblique angle, ℓ_z is the reduced-equivalent zenith path, and δ is the zenith angle. A

plot of m vs δ (and vs the elevation angle $\theta = 90^\circ - \delta$) is given in Fig. 2. The ultimate source of the values is Bemporad (Smithsonian, 1951).

1.2.2 Gaseous Attenuation

In the frequency range of 1 to 350 GHz, which will be referred to as microwave frequencies, absorption and emission by atmospheric gases can significantly affect earth-space telecommunications. Absorption by atmospheric gases is dominated by water-vapor lines at 22.235 GHz, 183.31 GHz, and 325.152 GHz, and by oxygen lines near 60 GHz and at 118.75 GHz. Nonresonant absorption by water vapor and oxygen also has a significant effect in the window regions between and below these lines. Ozone has narrow lines above 100 GHz that to a first approximation can be ignored, and will be in the material to follow. For a discussion of these lines and those of other minor constituents see, for example, Waters (1976). A thorough study and description of an existing computer program of water-vapor and oxygen attenuation and dispersion pertinent to earth-space communication for frequencies of 1 to 1000 GHz and altitudes of 0 to 100 km is available in Liebe (1981). Spectroscopic information on atmospheric constituents including pollutants is given in McClatchey, et al. (1973, 1976), and more recently in Poynter and Pickett (1980).

The absorption coefficient for each molecular species is a complex function of temperature, pressure, and frequency; see, for example, Waters (1976). However, once determined, the total absorption A for a path through the atmosphere is given quite simply by

$$A = \int_0^\infty \sum_i \gamma_i(T, p, f) \, d\ell \quad (7)$$

where γ_i is the absorption coefficient in nepers per meter (or kilometer) or in dB per meter (or kilometer) of the i^{th} gaseous

constituent. (Here the neper is used as the unit of optical depth; consequently, 1 neper = 4.34 dB rather than the traditional engineering usage of 1 neper = 8.68 dB.) For the purposes of this paper only two gaseous absorbers are considered: molecular oxygen and water vapor. Therefore, (7) becomes

$$A = \int_0^{\infty} \{ \gamma_o(T,P,f) + \gamma_w(T,P,f) \} dl \quad (8)$$

where γ_o and γ_w are the absorption coefficients for oxygen and water vapor respectively, which for the purposes of this report will be given in dB/km.

1.2.3 CCIR Gaseous Attenuation Curves

Following each Plenary Assembly of the CCIR (which have recently been taking place every four years), the approved texts (Recommendations, Reports, Study Programs, Questions, etc.) are published in three languages: French, English, and Spanish. The English volumes have green covers and are known as the CCIR Green Books. Because the CCIR is the technical advisory organ of the International Telecommunication Union in matters of radio, these Green Books provide the technical resource materials for the Union's Radio Regulations (which have treaty status). Consequently, the material in the Green Books tends to be treated as the international standard for those areas of radio which are covered by them. The basic CCIR propagation curves for the gaseous atmosphere are found in Report 719 (CCIR, 1978a). Three sets of curves were selected from Report 719 for attention, and are reproduced as Figs. 3, 4 and 5 of this report. In Fig. 3, the attenuation coefficient is given in one curve for a temperature of 20°C and pressure of 1013.25 mb, for 7.5 g/m³ of water vapor (43% relative humidity). The coefficient is given in a second curve for a dry atmosphere (labeled O₂) for frequencies of 0 to 350 GHz. Figure 4 gives the total one-way zenith attenuation through the atmosphere for a

frequency range of 0 to 300 GHz. The two curves are for the same parameters as Fig. 3, namely zero water vapor and 7.5 g/m^3 water vapor (at the surface) for a starting elevation from 0 to 16 km in 4-km increments.

1.2.4 Brightness Temperature

When in local thermodynamic equilibrium (LTE), the emission from a gas must equal its absorption, and by Kirchhoff's law this applies for any frequency. The Earth's atmosphere is in LTE for these purposes and emits radio noise at microwave frequencies in direct relation to the amount it absorbs. The sky-noise temperature in a given direction is known as the brightness temperature, T_B , and is given by the pertinent equation from radiative transfer theory (Waters, 1976):

$$T_B = \int_0^\infty T(\ell_i) \gamma(o, \omega) e^{-\tau(\ell_i, o)} d\ell + T_\infty e^{-\tau_\infty} \quad (9)$$

where $T(\ell)$ is the local ambient temperature, $\gamma(o, \omega)$ is the local absorption coefficient,

$$\tau(\ell_i, o) = \int_0^{\ell_i} \gamma(o, \omega) d\ell$$

is the optical depth between the emitting element and the receiver, and $T_\infty e^{-\tau_\infty}$ is the temperature from outside the atmosphere, in the direction in question, reduced by the optical depth through the atmosphere in that direction. In the discussion to follow, $T_\infty e^{-\tau_\infty}$ (normally less than 3 K) will be ignored.

Brightness temperature in the CCIR is given in Report 720 (CCIR, 1978b). Figures 1, 2, and 3 of that report appear as Figs. 6, 7, and 8 of this report. They apply to surface water-vapor densities of 3, 10, and 17 g/m³ respectively for a surface temperature of 20°C.

SECTION 2

INTERNAL CONSISTENCY

The curves of Figs. 3 through 8 form an interrelated set in that all are functions of atmospheric absorption. Two tests for internal consistency can be designed for such a set. First, the zenith attenuation for the dry (O_2) atmosphere of Fig. 4, when divided by the specific attenuation of O_2 at the surface (Fig. 3), should yield the oxygen-absorption scale height (about 5.4 km) away from absorption lines. Second, for optical depths, τ , much less than one (say less than 1 dB), the brightness temperature may be approximated by the equation (derived from the first term of the series expansion of $\exp[-\tau]$):

$$T_b \cong 60 [A \text{ (dB)}] \quad \tau \ll 1 \quad (10)$$

and for larger values of τ by

$$T_b \cong T_m (1 - e^{-\tau}) \quad (11)$$

where T_m is a mean temperature for the atmosphere, say, 280 K, and $\tau = A(\text{dB})/4.34$.

2.1 THE SCALE HEIGHT TEST

When the zenith attenuation of curve B (dry atmosphere) in Fig. 4 is divided for each frequency by the specific attenuation for O_2 from Fig. 3, the resultant equivalent thickness of the atmosphere (or scale height) for O_2 absorption is given in Fig. 9, and can be seen to fluctuate between 2.3 and 9 km (away from the 60- and 118-GHz absorption lines). When the same thing is done to the equivalent data derived from the JPL radiative-transfer program (Waters, 1976), the curve of Fig. 10 results, where away from the lines the scale height varies between 5 and 6 km. Comparison of Figs. 9 and 10 leaves little doubt but that the latter is the more reasonable.

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2.2 BRIGHTNESS TEMPERATURE--ABSORPTION COMPARISON

When the zenith curves are selected from each of Figs. 6, 7, and 8 and plotted on a single chart, as in Fig. 11, a brightness temperature may be computed using (11) and values read from curve A (7.5 g/m^3 water vapor at the surface) of Fig. 4. This information is plotted on the same chart as the zenith brightness-temperature curves in Fig. 11. It can be seen that agreement is not bad below 50 GHz, but that above about 85 GHz the agreement deteriorates rapidly.

SECTION 3

COMPARISON OF CCIR AND JPL VALUES

3.1 THE JPL PROGRAM

The JPL radiative-transfer program (Waters, 1976; Poynter and Pickett, 1980) incorporates the Gaut-Reifenstein (1971) empirical adjustment for water vapor in the wings of the absorption lines (an additive correction term proportional to the square of the frequency). It also makes use of the Rosenkranz (1975) expression for the oxygen absorption coefficient that includes first-order coherence effects of overlapping lines (Waters, 1976).

3.2 COMPARISON OF GASEOUS ABSORPTION

While it is clear from Figs. 9 and 10 that there must be significant differences between the CCIR and JPL values for either specific attenuation or zenith attenuation, it is not obvious for which one. The natural assumption is that these differences would be in the zenith attenuation, as specific attenuation can be determined from ground-based measurements. This did not turn out to be the case, as is apparent in Figs. 12 and 13. As can be seen in Fig. 12 the JPL values are 70% higher in the wings of the H_2O (7.5 g/m^3) curve of specific attenuation, and the O_2 curve above 120 GHz decreases much more sharply as a function of increasing frequency for the JPL case than it does for the CCIR one. Further, it is clear in Fig. 13 that zenith attenuation is in pretty good agreement for curve A (7.5 g/m of water vapor), but that the "oxygen only" values (curve B) are significantly different above 120 GHz (as in the case of the values for specific attenuation).

The comparison of zenith attenuation for steps of 4 km in elevation above the surface (Fig. 5) is given in Fig. 14. An interesting feature of this comparison is that the percentage separation between the CCIR and JPL models increases with the elevation of the earth station.

3.3 COMPARISON OF BRIGHTNESS TEMPERATURE

For the brightness-temperature comparison the JPL radiative-transfer code was programmed for the 1962 U.S. standard model atmosphere (COESA, 1962) and for a water-vapor scale height of 2 km up to the tropopause. The results are shown in Figs. 15, 16, and 17 for surface densities of water vapor of 3, 10, and 17 g/m³ respectively. The arid climate case (3 g/m³) portrayed in Fig. 15 is seen to be in pretty good agreement up to 60 GHz, and to diverge for low elevation angles ($\theta < 20^\circ$) for higher frequencies. For the intermediate and moist atmosphere cases of Figs. 16 and 17 (10 g/m³ and 17 g/m³) divergence becomes significant above 20 GHz.

SECTION 4

CURVE SETS

4.1 JPL CLEAR-AIR ABSORPTION

The JPL radiative-transfer program can accommodate some eight model atmospheres. Two model atmospheres have been used in connection with this report. They are:

- (1) U.S. 1962 standard model atmosphere (COESA, 1962)
- (2) Tropical (15°N) model atmosphere (Valley, 1965:
Table 2.2)

The characteristics of these two model atmospheres are given in Tables 1 and 2 respectively. The U.S. standard model atmospheres for 1962 and 1976 are identical up to 50 km. According to Fig. 2, less than 10^{-3} of the mass of the atmosphere is above 50 km. Therefore, the difference between the two model atmospheres would not show up until the fourth decimal place, and would not be discernible in the plots given in this report. Hence the data derived from these two model atmospheres are used interchangeably. The tropical model atmosphere (15°N) is brought in to allow for a 17 g/m^3 density of water vapor. The two U.S. standard model atmospheres have surface temperatures of 288.1 K (15°C), which has a saturation water vapor density of 12.85 g/m^3 . The tropical model atmosphere has a surface temperature of 302.59 K (29.44°C) with a saturation water-vapor density of nearly 30 g/m^3 .

The JPL absorption curves for clear air consist of the following set:

Figure 18. Specific absorption (in this case synonymous with specific attenuation)

Figure 19. Total one-way zenith attenuation

Figure 20. Zenith attenuation with 4-km height increments

4.2 JPL BRIGHTNESS TEMPERATURE

The brightness temperature set contains four families of curves:

Figure 21. Zenith brightness temperature for 0, 3, 10, and 17 g/m³ water vapor

Figure 22. Brightness temperature for 7.5 g/m³ water vapor for frequencies of 1-50 GHz

Figure 23. Brightness temperature for 3 g/m³ water vapor for frequencies of 1-340 GHz

Figure 24. Brightness temperature for 7.5 g/m³ water vapor for frequencies of 1-340 GHz

Figure 25. Brightness temperature for 17 g/m³ water vapor for frequencies of 1-340 GHz

The tropical model atmosphere is used for Fig. 25; the others use the U.S. 1962 standard model atmosphere (taken here to be equivalent to the 1976 one).

SECTION 5

CONCLUSION

The atmospheric attenuation and brightness temperature data of CCIR Reports 719 and 720 (CCIR, 1978a,b) have been shown to have internal consistency problems. A comparable set prepared from the JPL radiative-transfer program does not suffer these problems, includes more modern information, and is documented. The JPL set is recommended over the CCIR (1978) set.

The CCIR, of course, does not stand still. The problems with the 1978 versions of Reports 719 and 720 will be corrected in 1982 versions. Also, more sophisticated approaches have been incorporated in the proposed 1982 texts, so some of the CCIR curve sets which are used for comparison here are slated to disappear in the future (CCIR, 1982a,b).

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Table 1. Atmospheric Model Used in All Calculations With the JPL Radiative-Transfer Program Except for Figure 25. Model Represents: - U.S. Standard Atmosphere, 1976 (0 to 50 km)
 - U.S. Standard Atmosphere, 1962 (0 to 75 km)
 Water vapor added to the model is 7.5 g/m^3 at the surface with 2-km scale height to 12 km, standard water vapor above.

HT (KM)	PRES. (MB.)	TEMP. (K)	DENS. (CM**=3)	VOLUME MIXING RATIOS	
				H2O	O2
75.00	.2417-01	208.40	.8400+15	.2837-05	.2100+00
72.50	.3578-01	213.33	.1215+16	.4126-05	.2100+00
70.00	.5220-01	219.60	.1722+16	.6000-05	.2100+00
67.50	.7654-01	226.45	.2448+16	.6000-05	.2100+00
65.00	.1103+00	233.25	.3425+16	.6000-05	.2100+00
62.50	.1566+00	240.12	.4725+16	.6000-05	.2100+00
60.00	.2195+00	247.00	.6438+16	.6000-05	.2100+00
57.50	.3088+00	253.87	.8810+16	.6000-05	.2100+00
55.00	.4285+00	260.75	.1190+17	.6000-05	.2100+00
52.50	.5873+00	267.62	.1590+17	.6000-05	.2100+00
50.00	.7974+00	270.60	.2135+17	.6000-05	.2100+00
47.50	.1095+01	269.67	.2942+17	.6000-05	.2100+00
45.00	.1504+01	264.15	.4124+17	.6000-05	.2100+00
42.50	.2073+01	257.27	.5838+17	.6000-05	.2100+00
40.00	.2870+01	250.30	.8307+17	.6000-05	.2100+00
37.50	.4074+01	243.42	.1212+18	.5449-05	.2100+00
35.00	.5808+01	236.50	.1779+18	.4949-05	.2100+00
32.50	.8324+01	229.80	.2624+18	.4495-05	.2100+00
30.00	.1197+02	226.50	.3828+18	.4082-05	.2100+00
27.50	.1759+02	224.00	.5687+18	.3708-05	.2100+00
25.00	.2580+02	221.55	.8434+18	.3367-05	.2100+00
22.50	.3778+02	219.10	.1249+19	.3058-05	.2100+00
20.00	.5528+02	216.60	.1849+19	.3000-05	.2100+00
17.50	.8258+02	216.60	.2762+19	.3000-05	.2100+00
15.00	.1226+03	216.60	.4099+19	.3000-05	.2100+00
12.50	.1808+03	216.60	.6048+19	.7956-05	.2100+00
10.00	.2650+03	223.30	.8597+19	.1967-03	.2100+00
7.50	.3853+03	239.45	.1166+20	.5063-03	.2100+00
5.00	.5445+03	255.70	.1543+20	.1335-02	.2100+00
2.50	.7505+03	271.95	.1999+20	.3597-02	.2100+00
.00	.1013+04	288.10	.2547+20	.9854-02	.2100+00
-2.50					

Table 2. Tropical Atmosphere Model (15°N. Latitude).
 Water vapor added to the model is 17 g/m³
 at the surface with 2-km scale height to
 12 km, standard water vapor above that.

HT (KM)	PRES. (MB.)	TEMP. (K)	DENS. (CM**=3)	VOLUME MIXING RATIOS	
				H2O	O2
72.50	.3338+01	206.89	.1169+16	.4126-05	.2100+00
70.00	.5002+01	215.64	.1680+16	.6000-05	.2100+00
67.50	.7375+01	224.39	.2381+16	.6000-05	.2100+00
65.00	.1071+00	233.14	.3329+16	.6000-05	.2100+00
62.50	.1535+00	241.90	.4597+16	.6000-05	.2100+00
60.00	.2171+00	250.65	.6275+16	.6000-05	.2100+00
57.50	.3038+00	257.15	.8559+16	.6000-05	.2100+00
55.00	.4222+00	262.15	.1167+17	.6000-05	.2100+00
52.50	.5830+00	267.15	.1581+17	.6000-05	.2100+00
50.00	.8006+00	270.15	.2147+17	.6000-05	.2100+00
47.50	.1098+01	270.15	.2945+17	.6000-05	.2100+00
45.00	.1510+01	265.75	.4115+17	.6000-05	.2100+00
42.50	.2089+01	260.25	.5814+17	.6000-05	.2100+00
40.00	.2911+01	254.75	.8276+17	.6000-05	.2100+00
37.50	.4085+01	249.25	.1187+18	.5449-05	.2100+00
35.00	.5776+01	243.75	.1717+18	.4949-05	.2100+00
32.50	.8233+01	238.25	.2503+18	.4495-05	.2100+00
30.00	.1183+02	232.75	.3683+18	.4082-05	.2100+00
27.50	.1715+02	227.25	.5468+18	.3708-05	.2100+00
25.00	.2510+02	221.75	.8198+18	.3367-05	.2100+00
22.50	.3707+02	216.25	.1242+19	.3058-05	.2100+00
20.00	.5545+02	207.15	.1939+19	.3000-05	.2100+00
17.50	.8461+02	197.15	.3109+19	.3000-05	.2100+00
15.00	.1306+03	203.20	.4655+19	.3000-05	.2100+00
12.50	.1956+03	219.95	.6441+19	.7956-05	.2100+00
10.00	.2835+03	236.60	.8681+19	.4415-03	.2100+00
7.50	.4020+03	253.10	.1150+20	.1163-02	.2100+00
5.00	.5574+03	269.60	.1498+20	.3118-02	.2100+00
2.50	.7580+03	286.09	.1919+20	.8491-02	.2100+00
.00	.1013+04	302.59	.2426+20	.2345-01	.2100+00
-2.50					

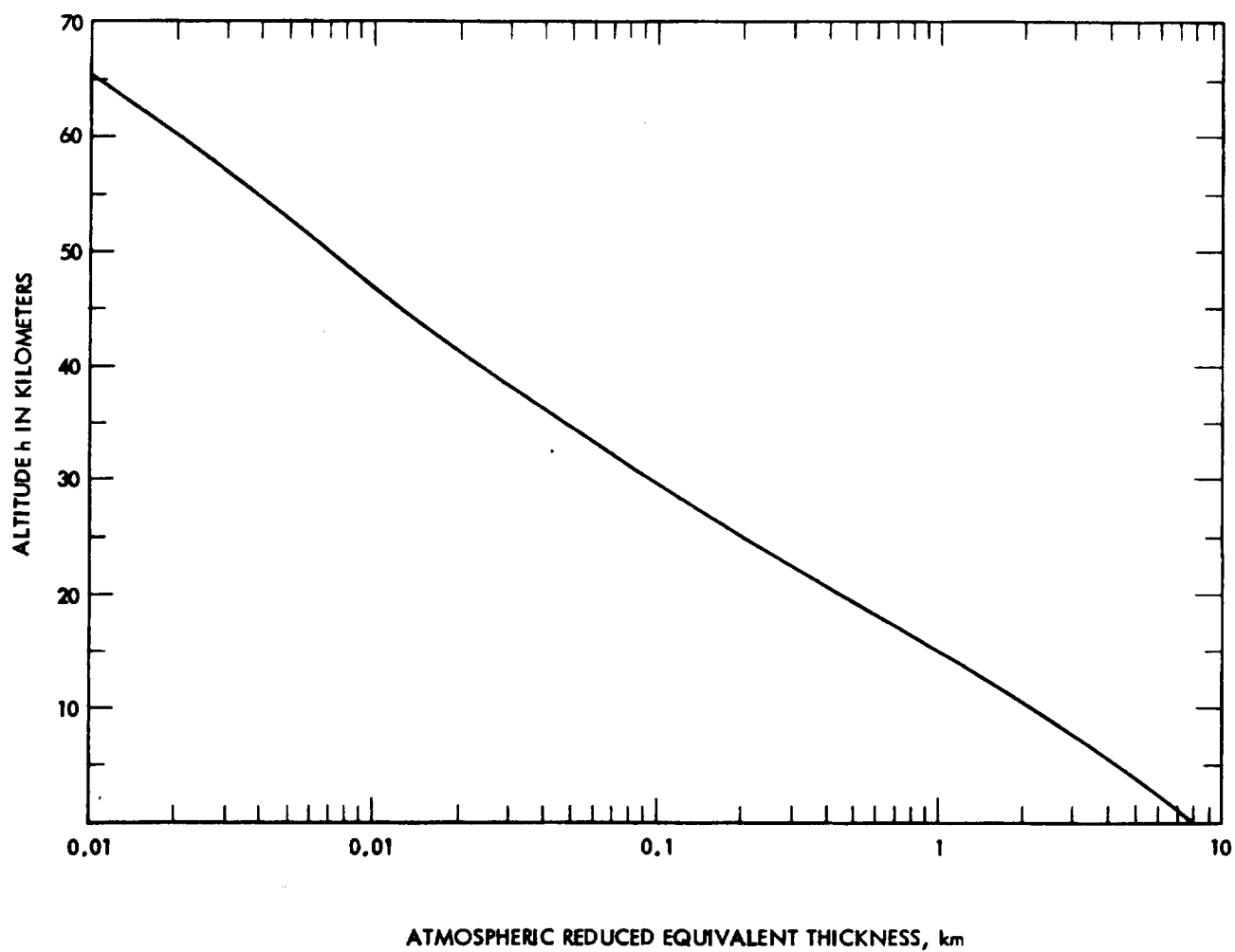


Figure 1. Atmospheric reduced-equivalent thickness above indicated altitude, surface at NTP (0°C , 1013 mb). Data from Valley (1965), Table 16-5.

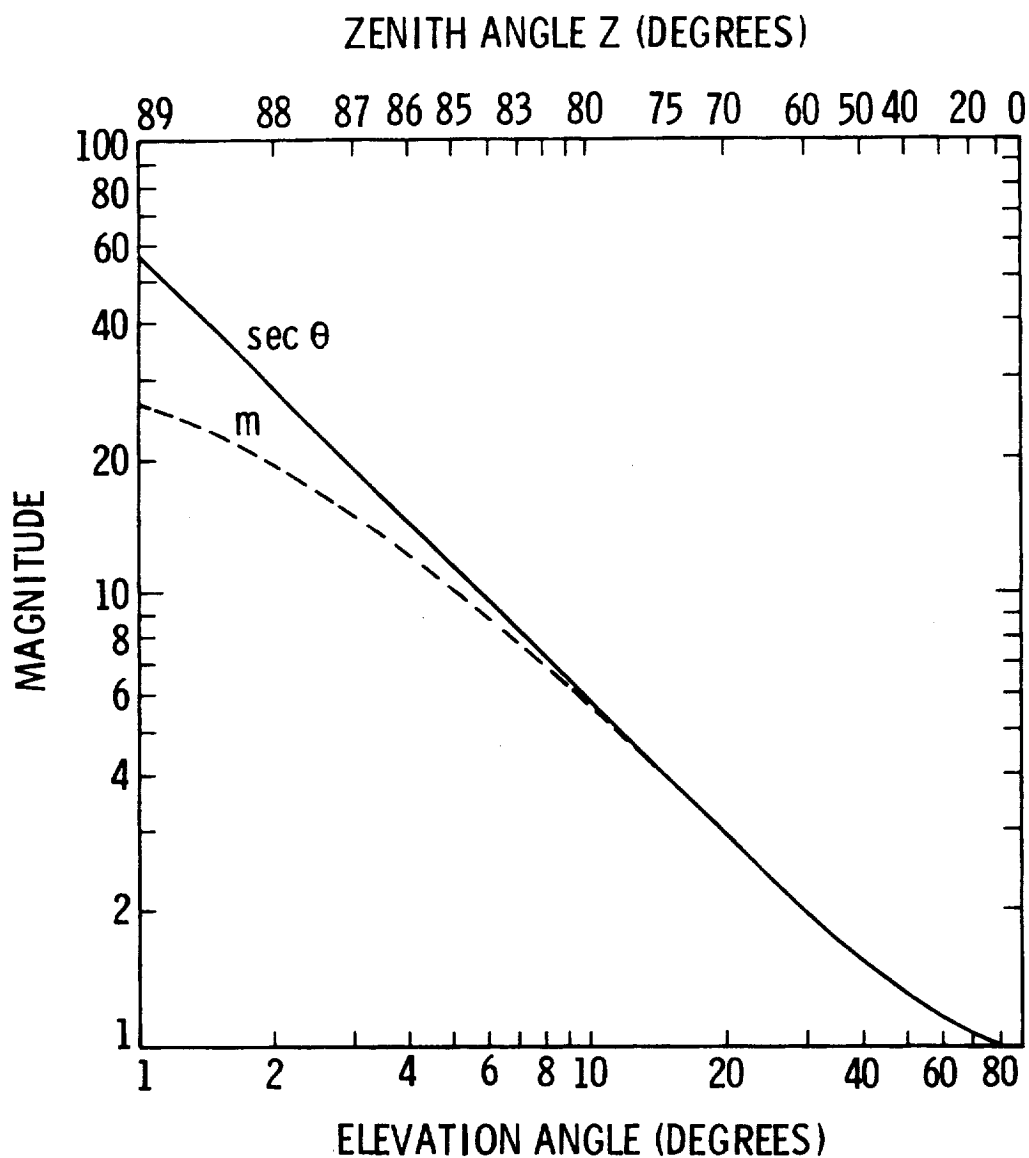


Figure 2. Variation of optical air mass (m), with elevation angle, for a ray traversing the atmosphere, compared to $\sec \theta$ and the Chapman Function for $Q = 1000$. Data from Gast (1957) and Allen (1976). (Illustrative only of refraction, due to the fact that water vapor is different at radio and optical frequencies.)

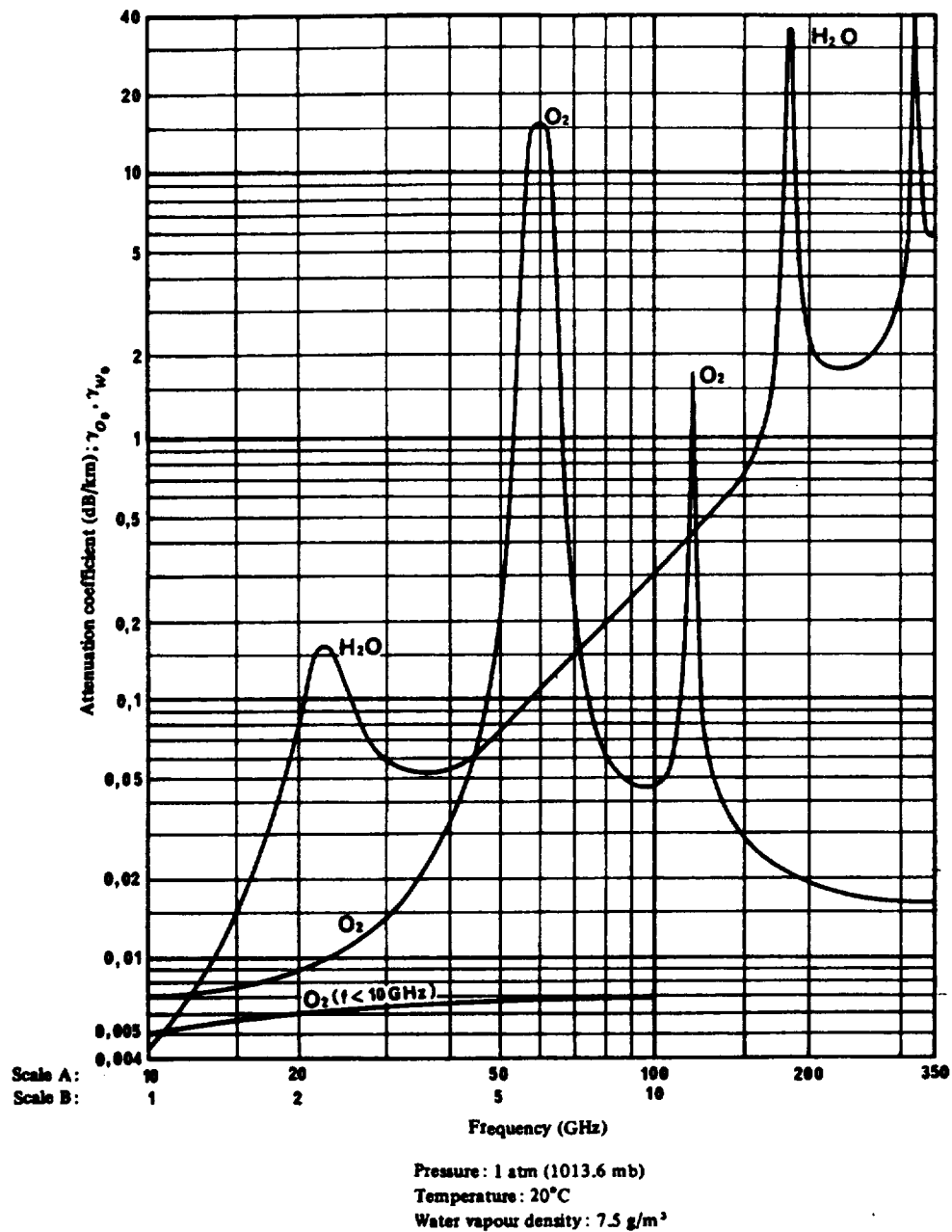


Figure 3. Specific attenuation by atmospheric gases--Fig. 1 of CCIR Report 719 (CCIR, 1978a). Use scale B for oxygen absorption below 10 GHz.

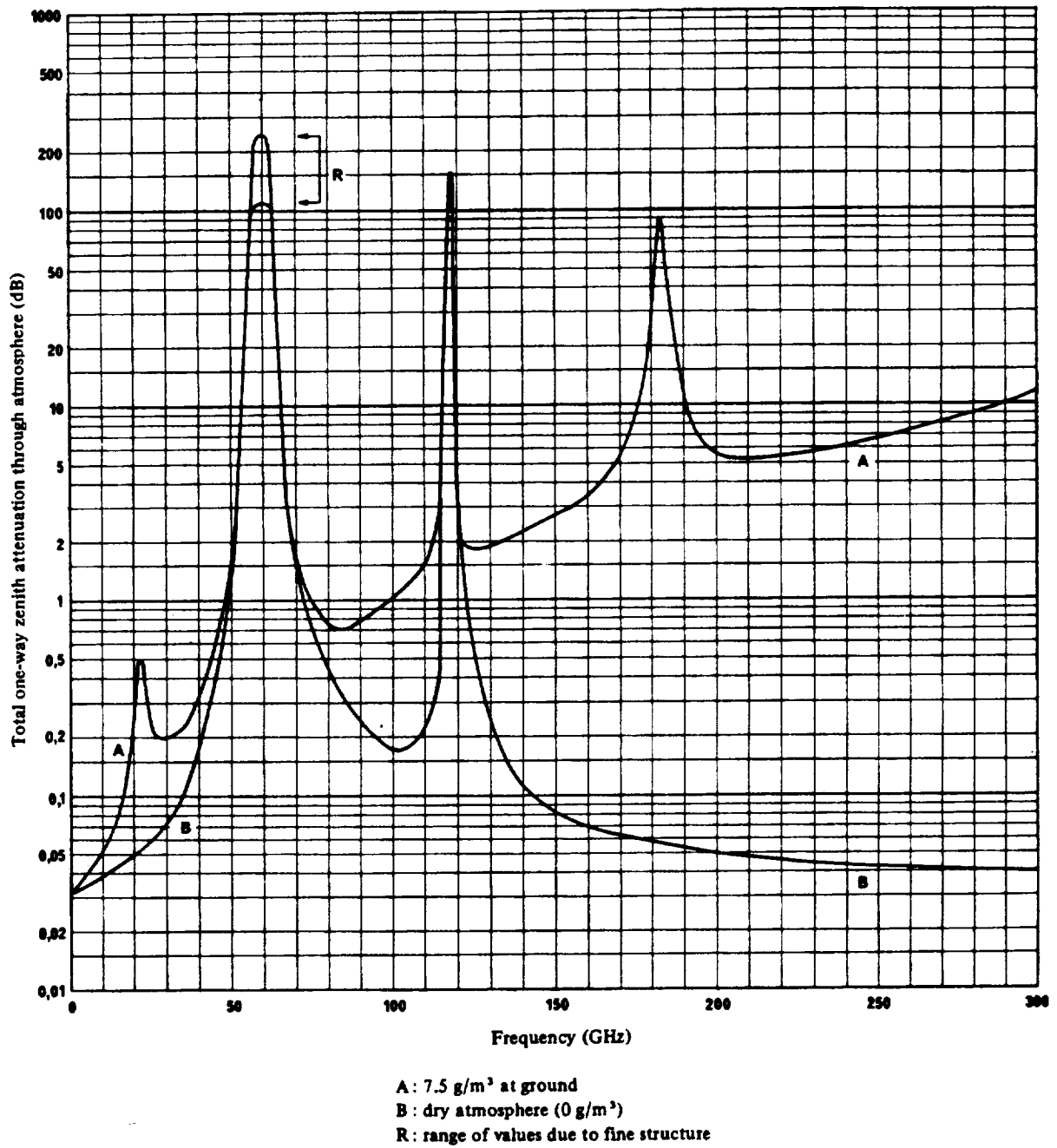
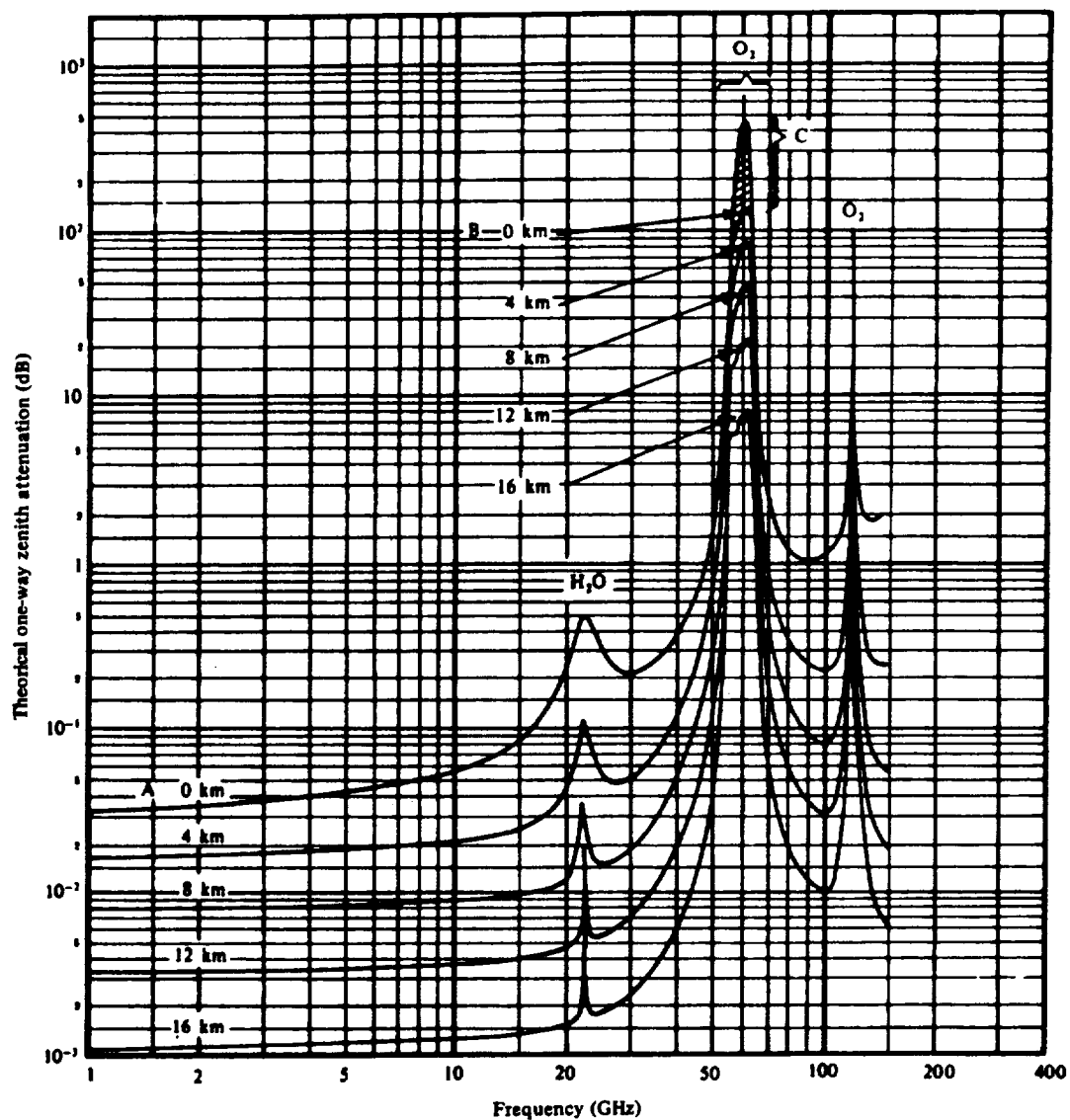


Figure 4. Total one-way zenith attenuation through the atmosphere--Fig. 2 of CCIR Report 719.



A: Starting heights (km)

B: Minimum values for paths starting at indicated heights (km)

C: Range of values for the path from the surface to 80 km altitude due to fine structure

Figure 5. Theoretical one-way attenuation from specified height to the top of the atmosphere--Fig. 3 of CCIR Report 719.

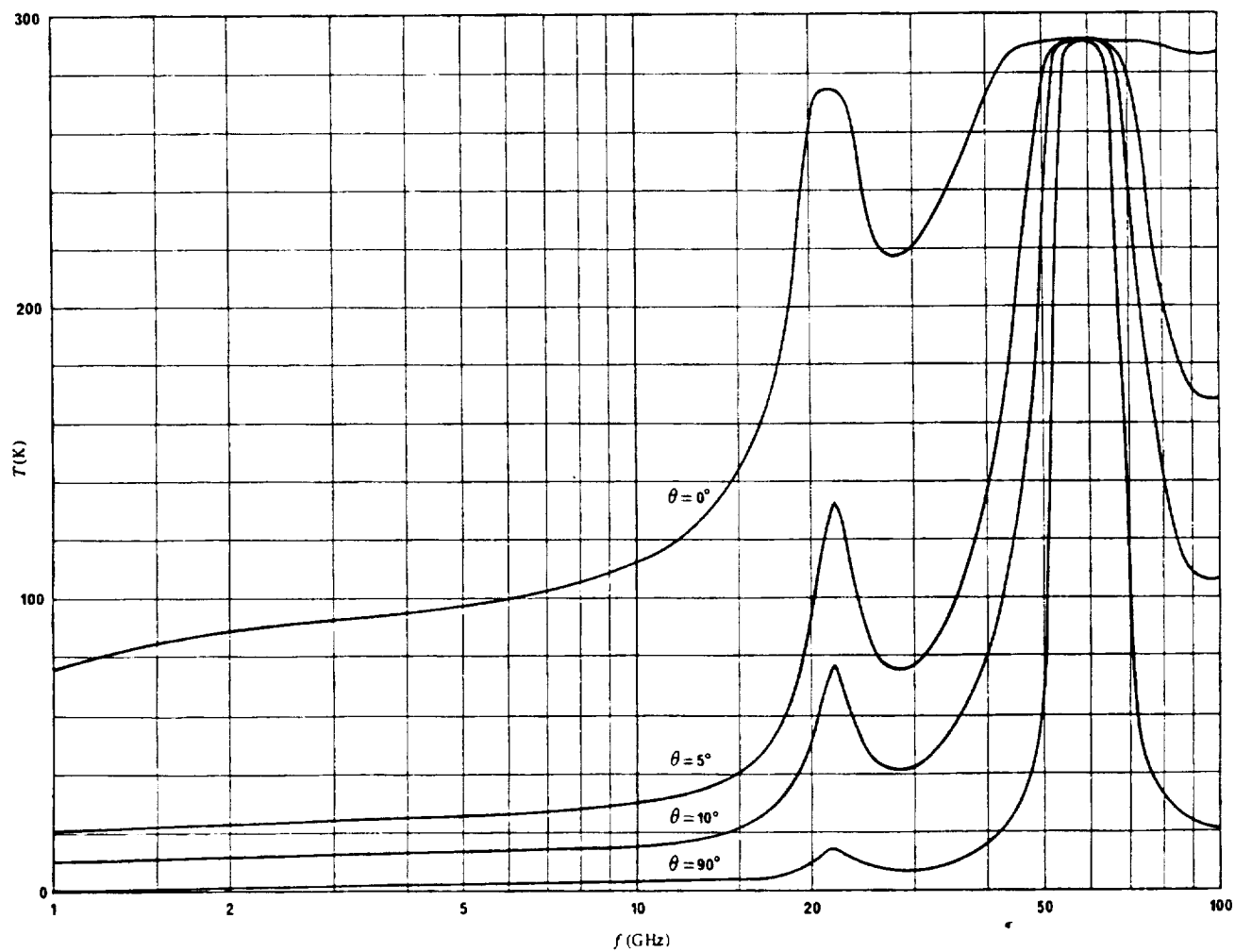


Figure 6. Sky noise temperature (clear air) for surface pressure of 1 atmosphere and temperature of 20°C and a surface water-vapor concentration of 3 g/m^3 --Fig. 1 of CCIR Report 720.

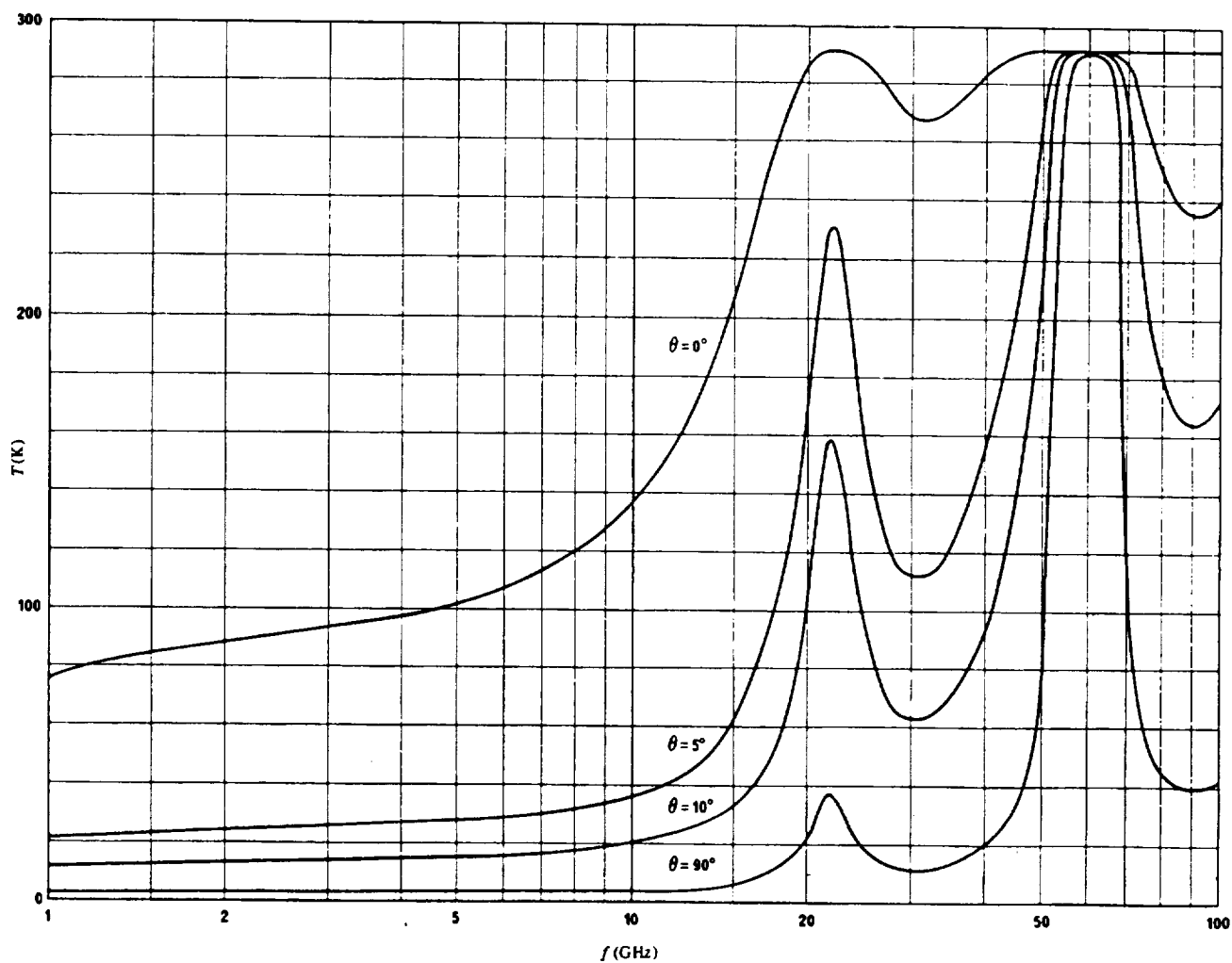


Figure 7. Sky noise temperature (clear air) for surface pressure of 1 atmosphere and temperature of 20°C and a surface water-vapor concentration of 10 g/m^3 --Fig. 2 of CCIR Report 720.

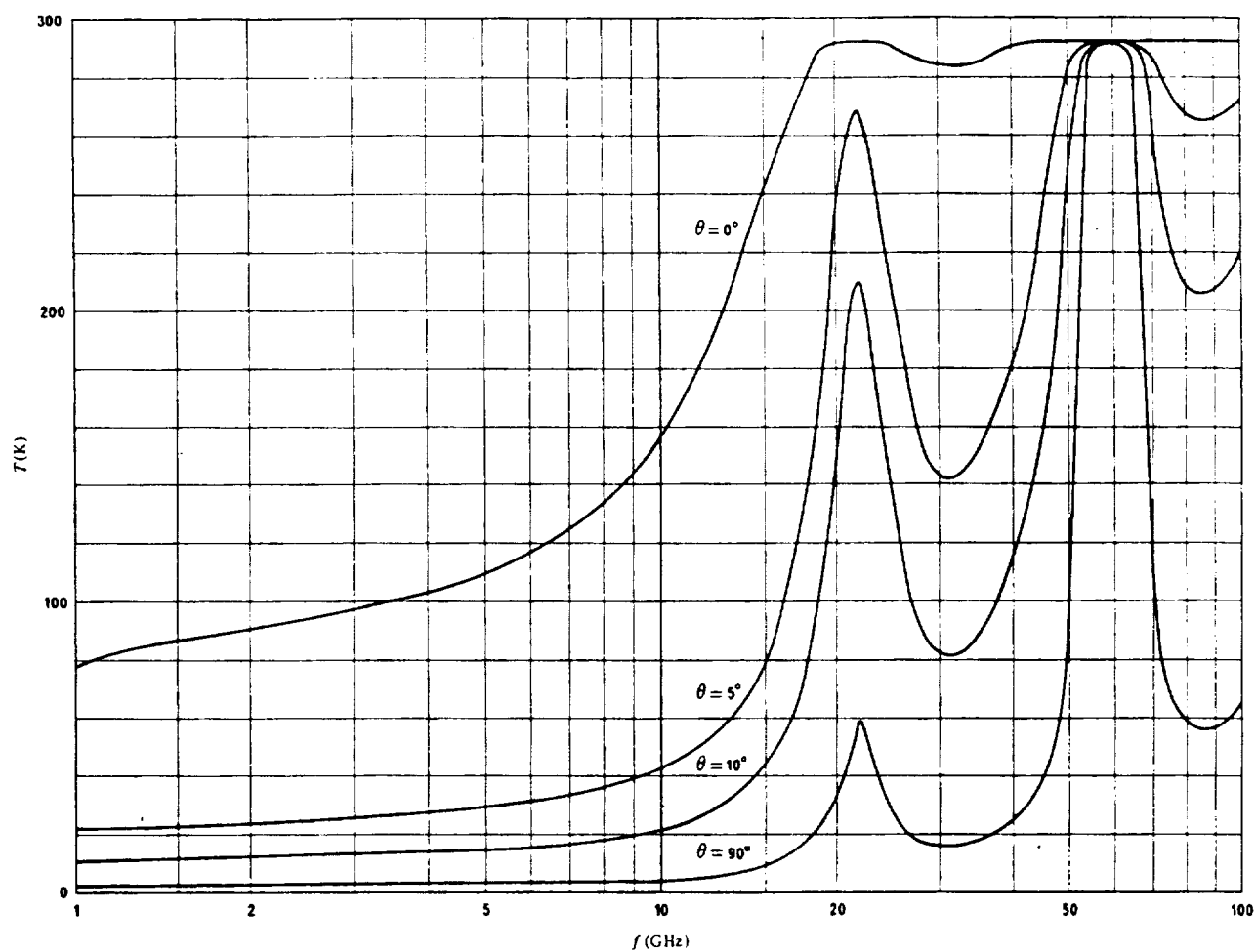


Figure 8. Sky noise temperature (clear air) for surface pressure of 1 atmosphere and temperature of 20°C and a surface water-vapor concentration of 17 g/m^3 --Fig. 3 of CCIR Report 720.

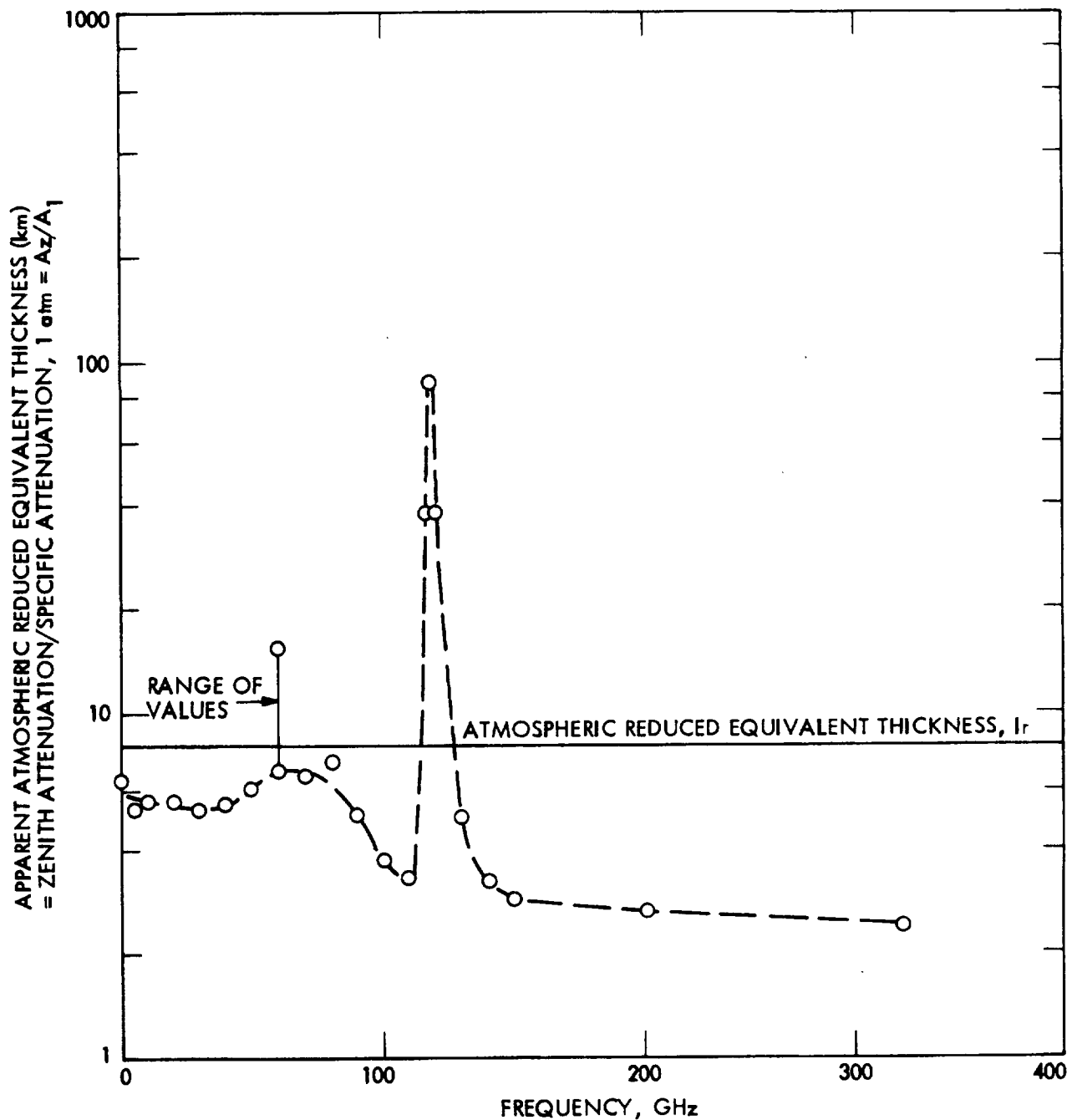


Figure 9. Apparent scale height for oxygen absorption in the atmosphere, derived by dividing the magnitude of curve B (dry atmosphere, i.e., 0 g/m^3 water vapor) of Fig. 4 by the attenuation coefficient (dB/km) at 1 atmosphere and 20°C for O_2 from Fig. 3.

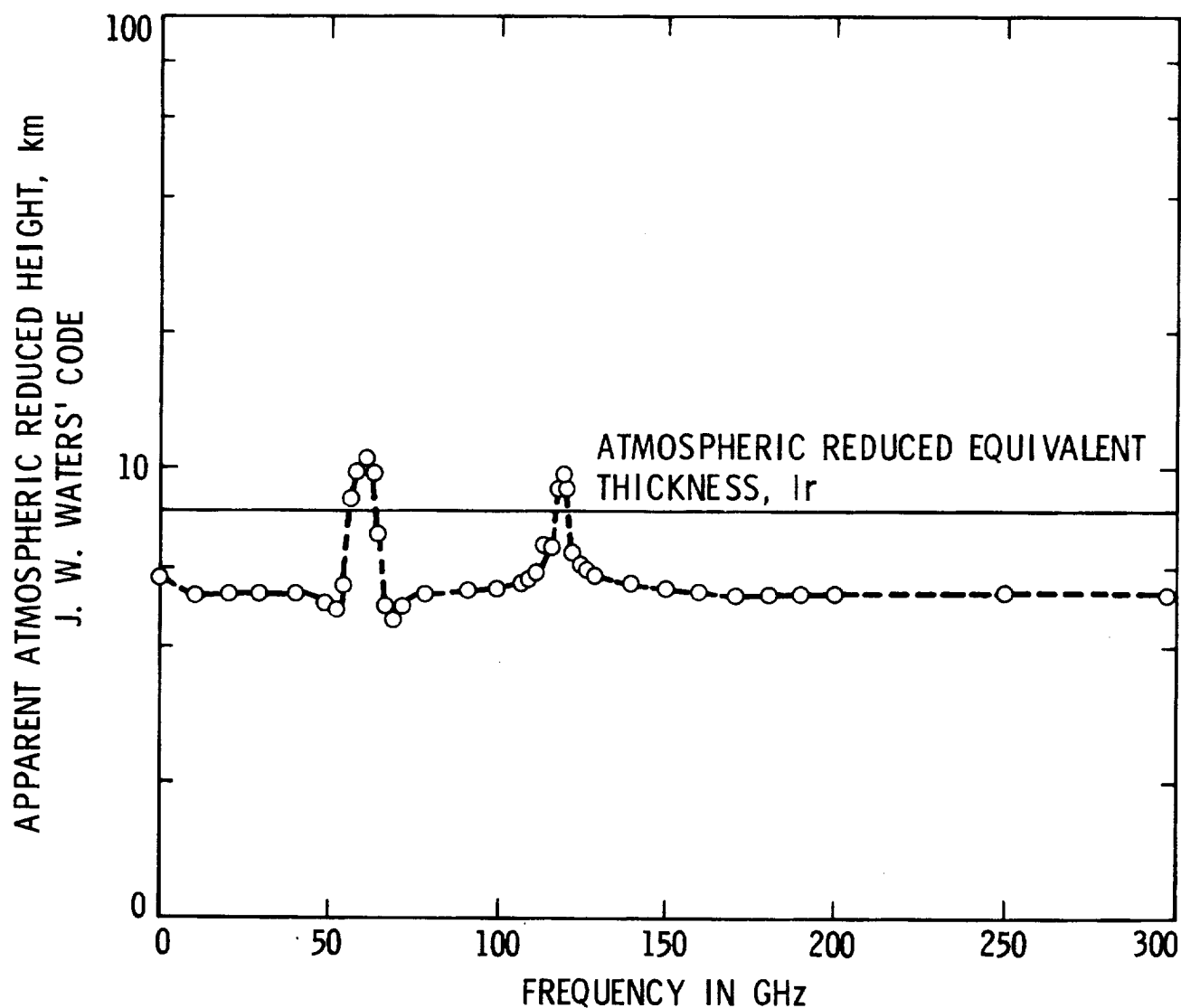


Figure 10. Comparison of apparent and true atmospheric reduced-equivalent thickness from JPL radiative-transfer program for quotient: zenith dry-atmospheric absorption by the specific absorption of O_2 from the same program.

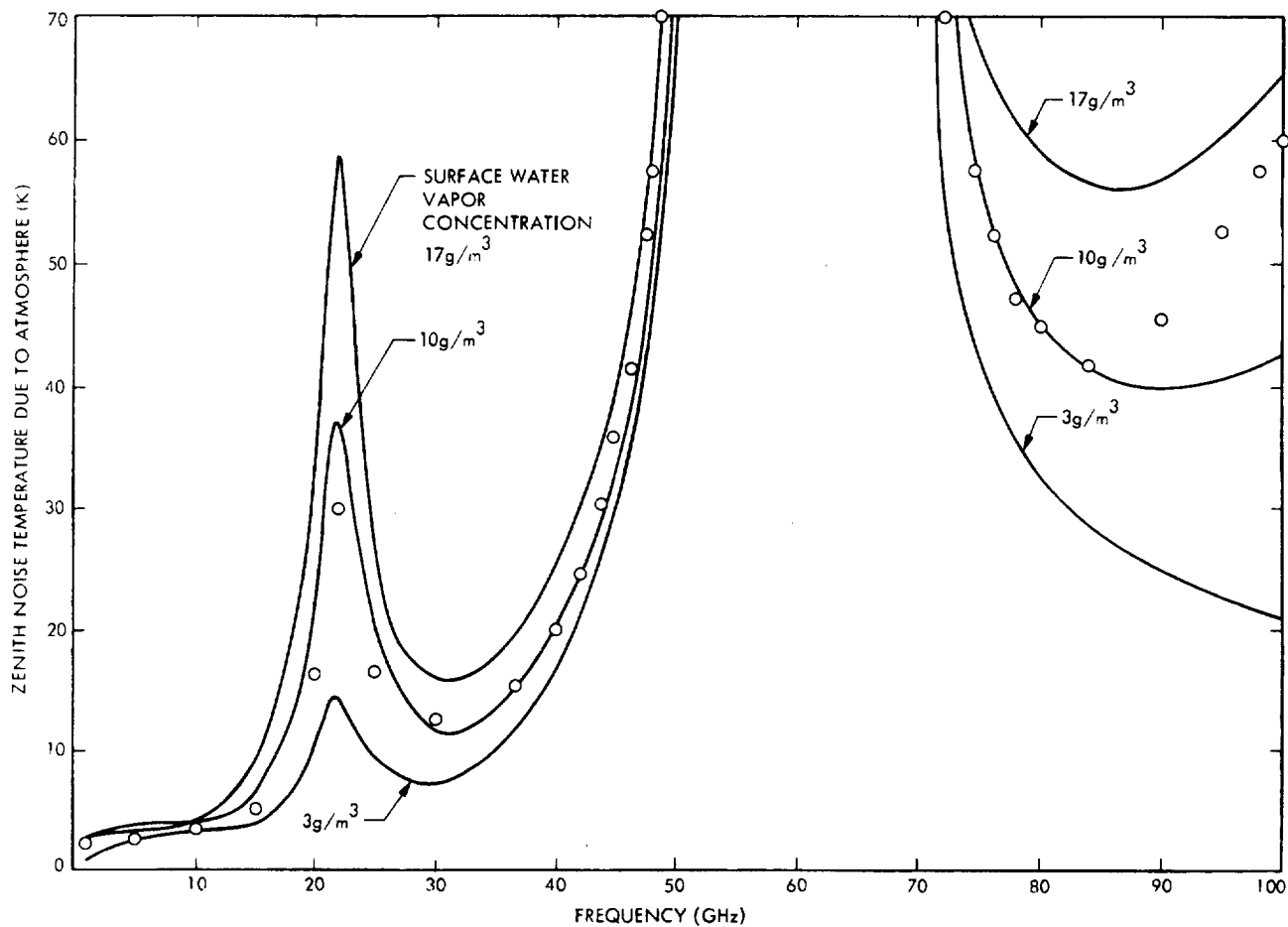


Figure 11. Zenith brightness temperature for 3, 10, and 17 g/m³ water vapor--taken from Figs. 1, 2, and 3 of Report 720 (CCIR, 1978b)--compared to brightness temperature derived from curve A of Fig. 2 of Report 719 (CCIR, 1978a).

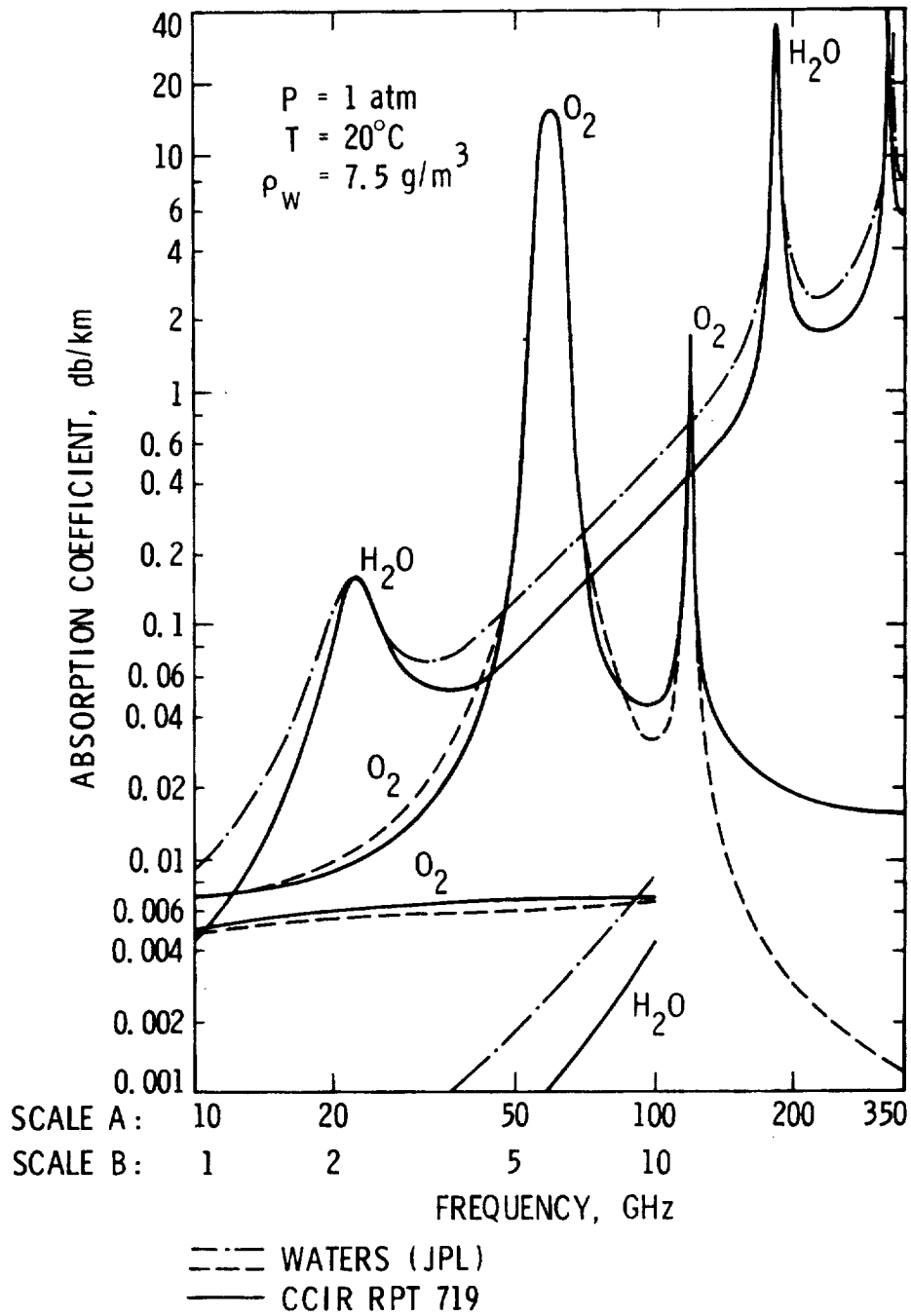


Figure 12. Comparison of specific attenuation by atmospheric gases as given in CCIR Report 719 (Fig. 3 of this report)--solid line--and as obtained from the JPL radiative transfer program--dashed and dot-dashed lines.

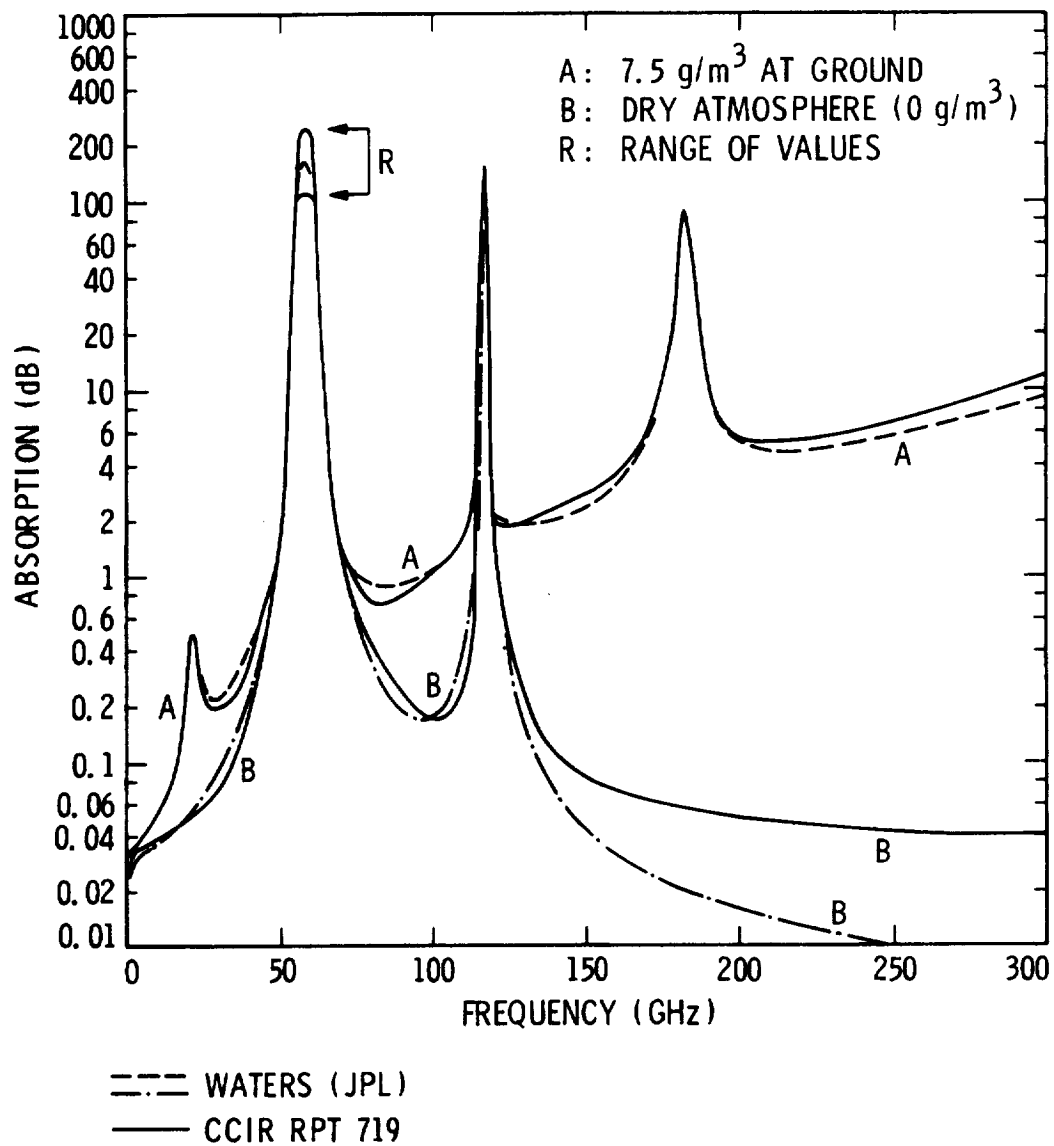
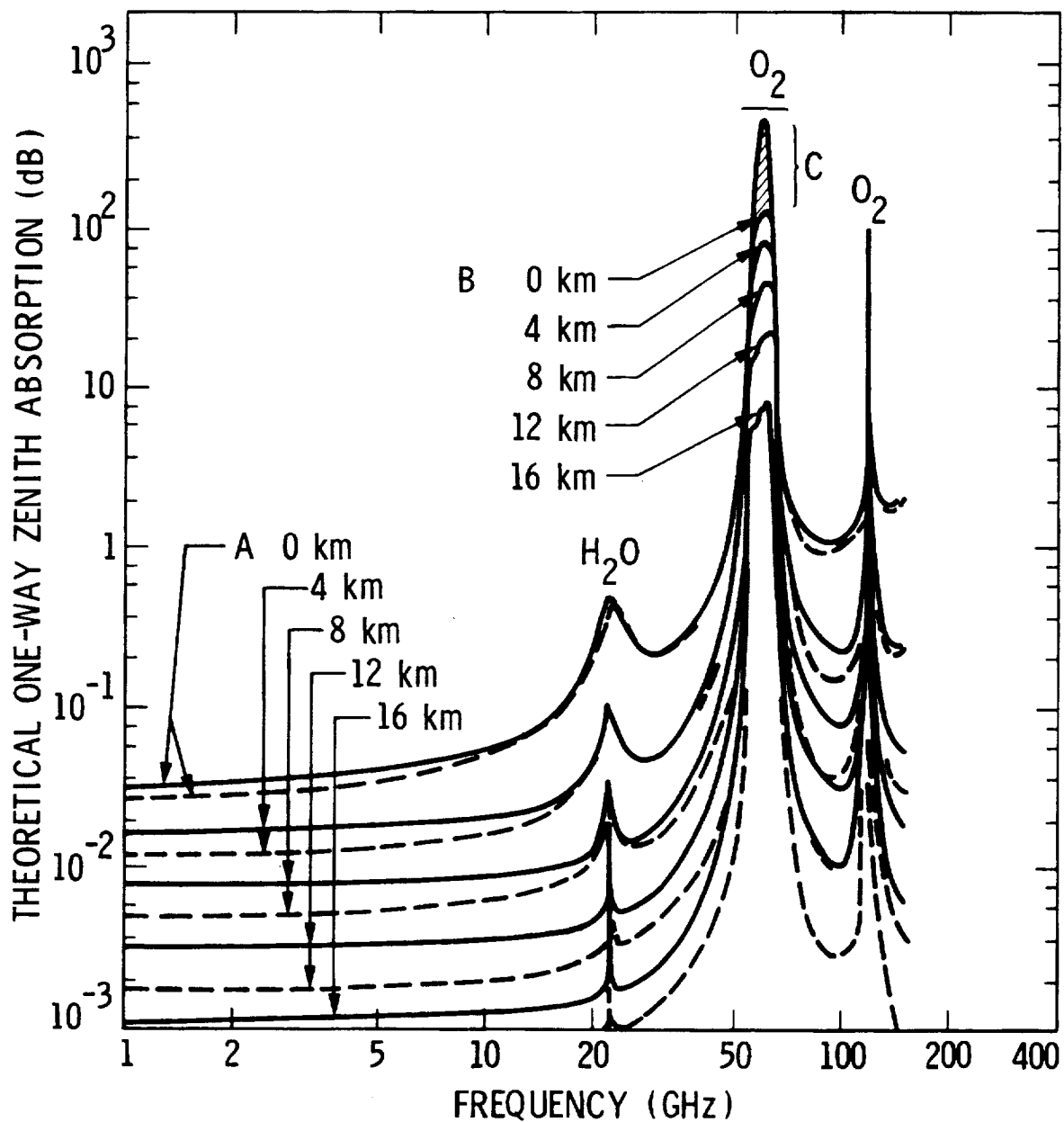


Figure 13. Comparison of zenith attenuation by the atmosphere (clear air) as given in CCIR Report 719 (Fig. 2 of this report)--solid line--and that obtained from the JPL radiative-transfer program--dashed line.



--- WATERS (JPL) — CCIR RPT 719

Figure 14. Comparison of zenith attenuation for various specified heights--Report 719, Figure 3 (CCIR, 1978a)--for CCIR vs the JPL radiative-transfer program. Water vapor is 7.5 g/m^3 at the surface with 2-km scale height. Surface temperature is 20°C . The JPL program uses the U.S. 1962 standard model atmosphere. (COESA, 1962).

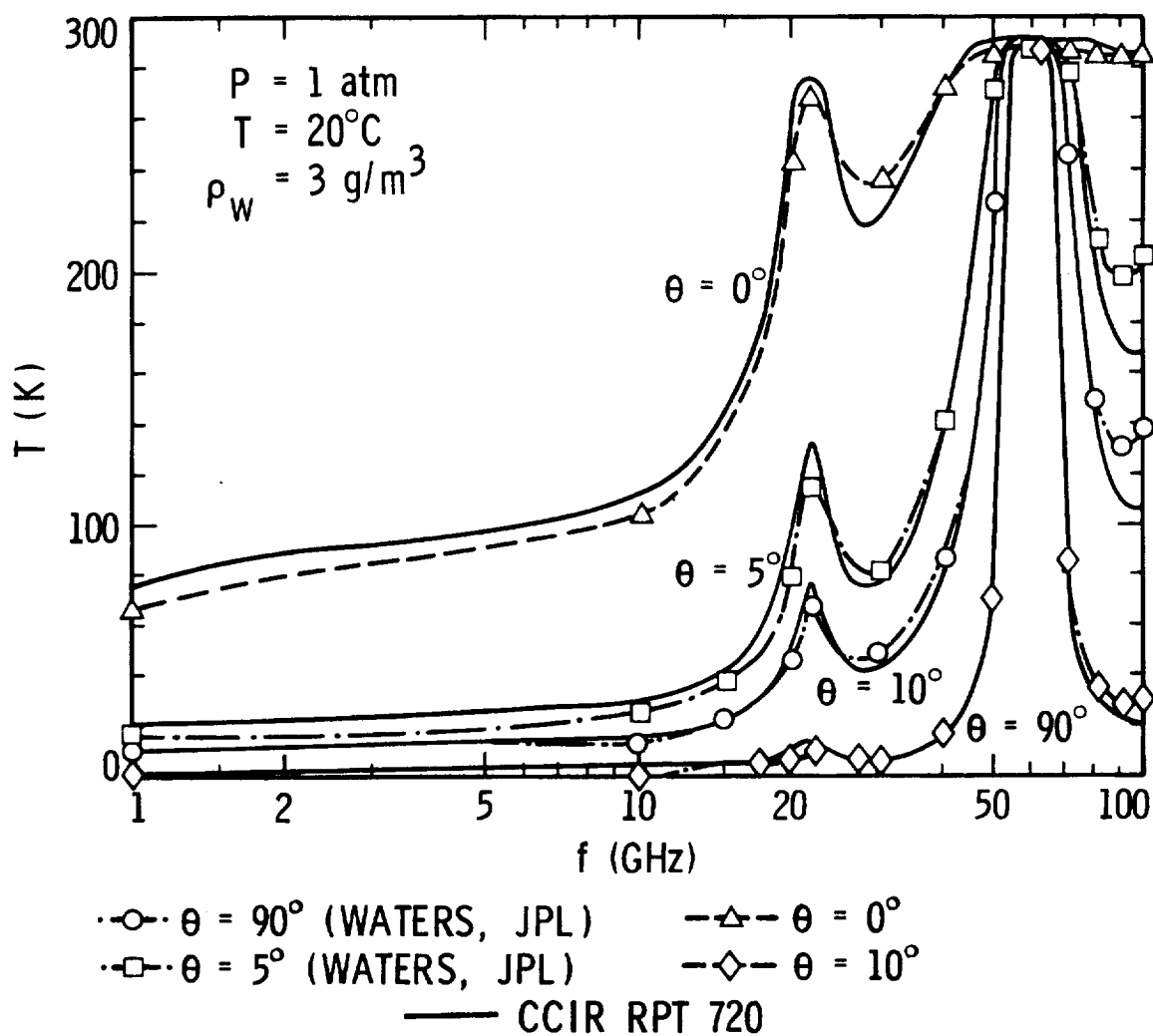


Figure 15. Comparison of CCIR--Report 720, Figure 1 (1978b)--and JPL brightness temperatures for an arid atmosphere ($3 \text{ g/m}^3 \text{ H}_2\text{O}$ at surface with scale height of 2 km).

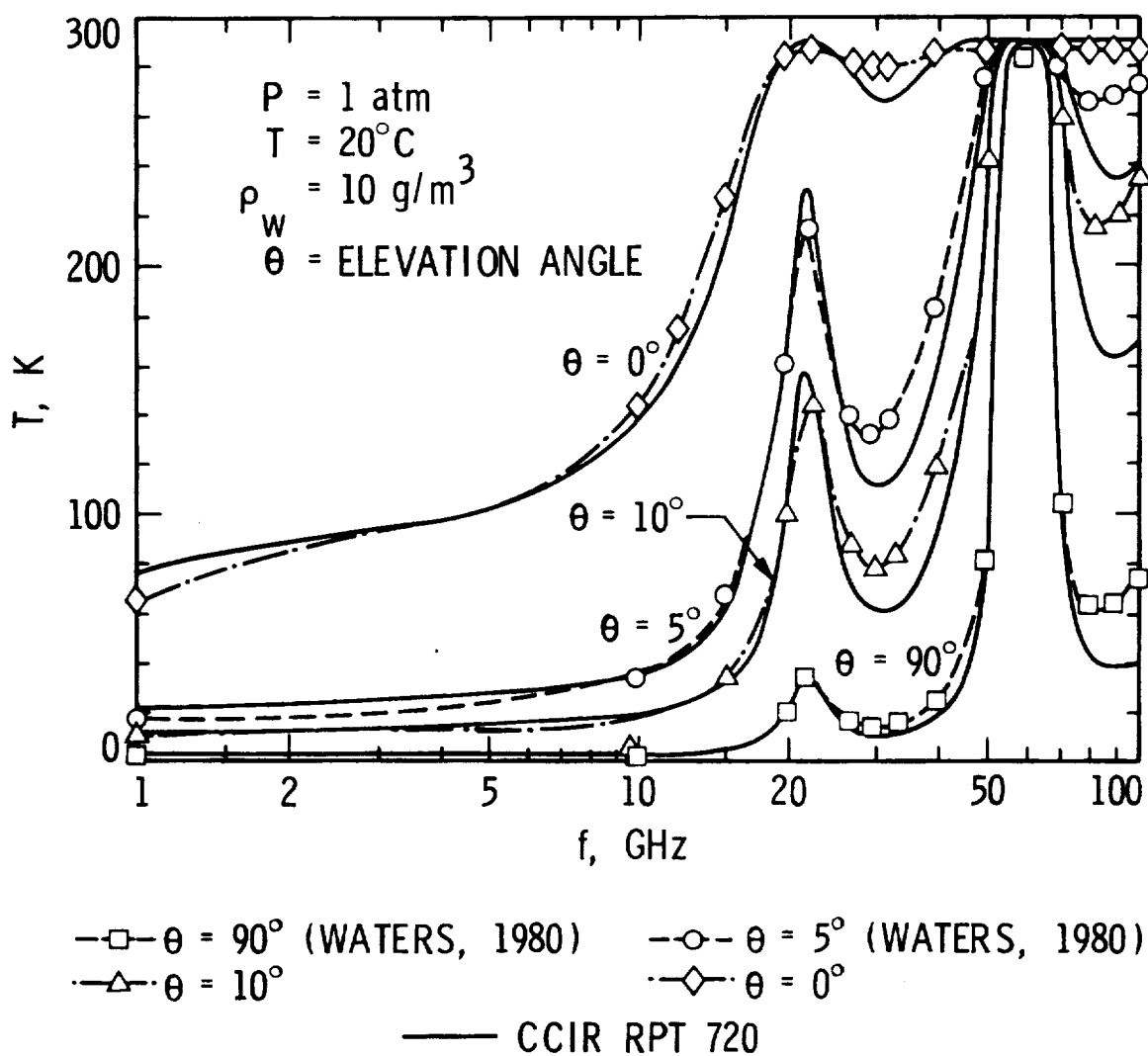


Figure 16. Comparison of CCIR--Report 720, Figure 2 (1978b)--and JPL brightness temperatures for an average atmosphere ($10 \text{ g/m}^3 \text{ H}_2\text{O}$ at surface with scale height of 2 km).

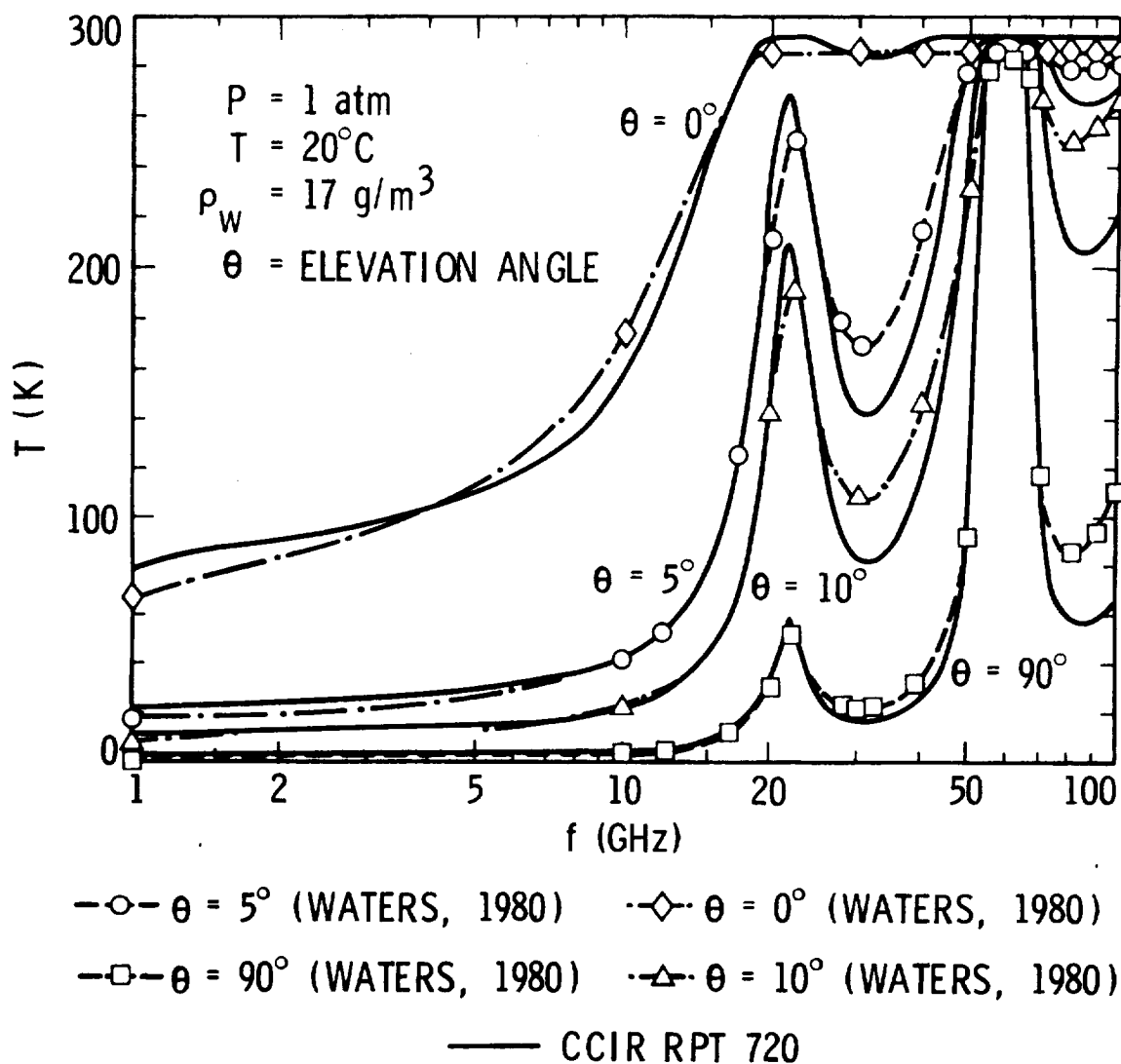


Figure 17. Comparison of CCIR--Report 720, Figure 3 (1978b)--and JPL brightness temperatures for a moist atmosphere ($17 \text{ g/m}^3 \text{ H}_2\text{O}$ at surface with scale height of 2 km).

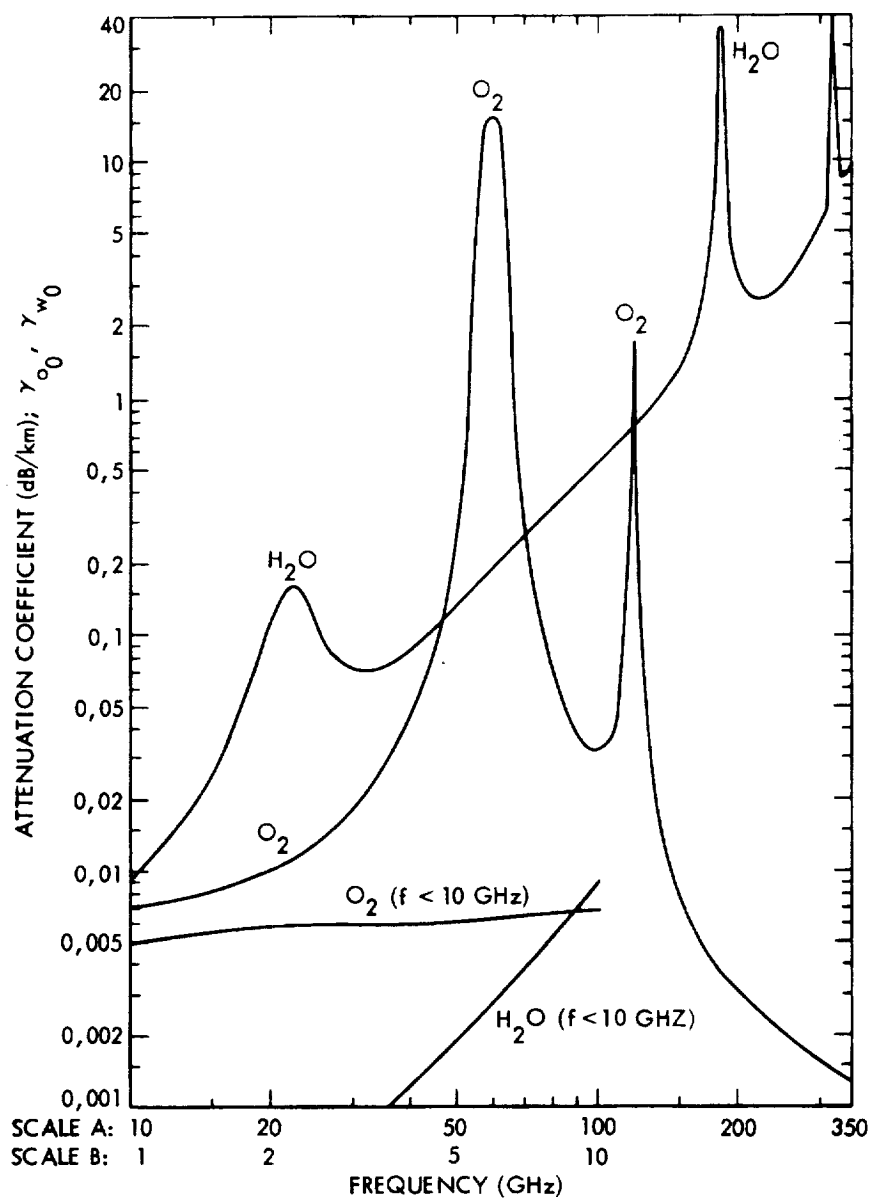


Figure 18. Specific attenuation (absorption) from the JPL radiative-transfer program for 290 K, 7.5 g/m^3 water vapor and dry (O_2) atmospheres, 1020.5 mb for the moist, and 1013 mb for the dry atmosphere (O_2); 1 to 340 GHz.

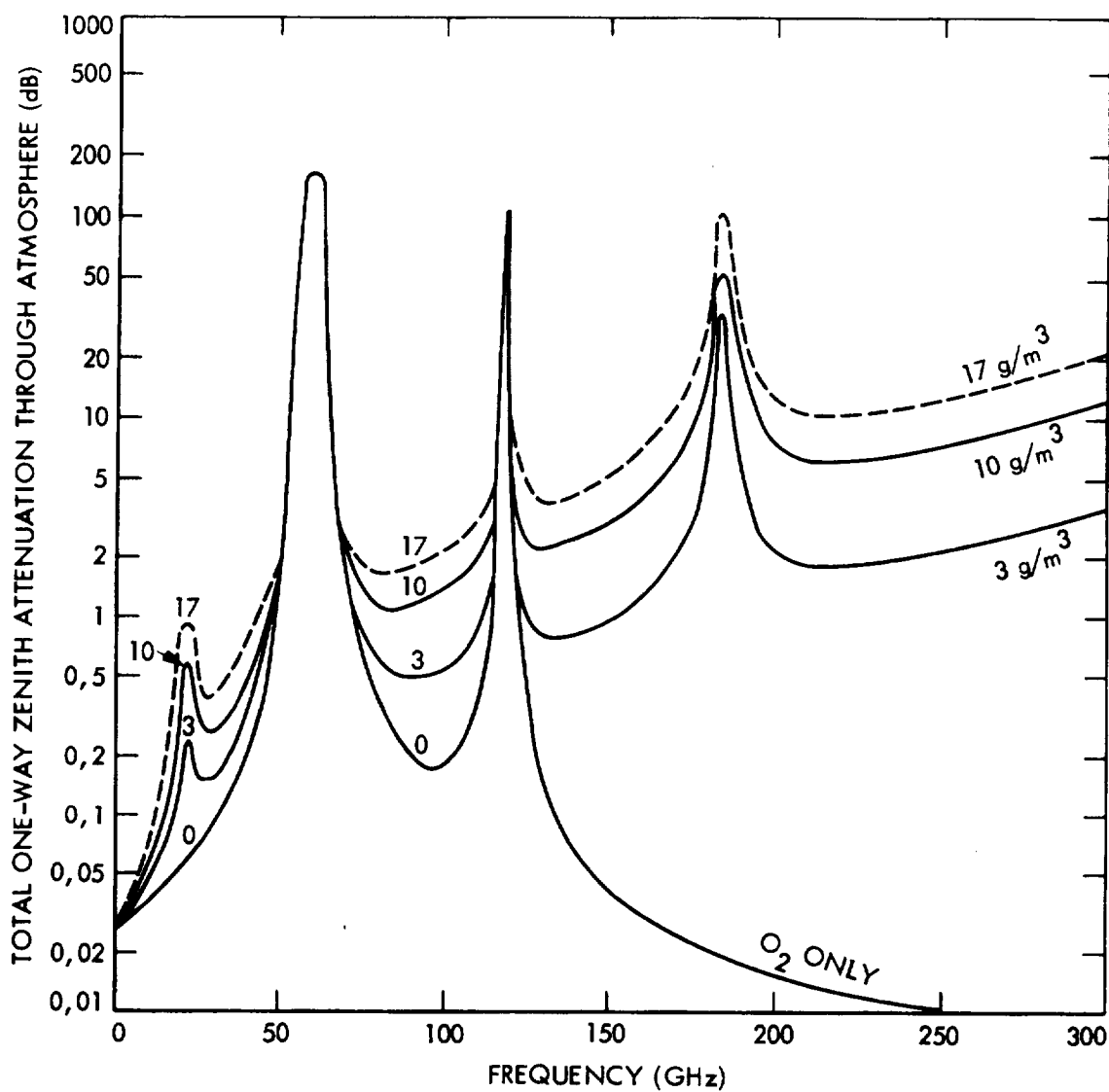


Figure 19. Total one-way zenith attenuation from the JPL radiative-transfer program for: the 1976 U.S. standard model atmosphere, 7.5 g/m^3 water vapor (2-km scale height) and O_2 atmospheres. Surface temperature 288 K, pressure 1020.5 for water vapor, 1013 for O_2 atmosphere, 1 to 340 GHz.

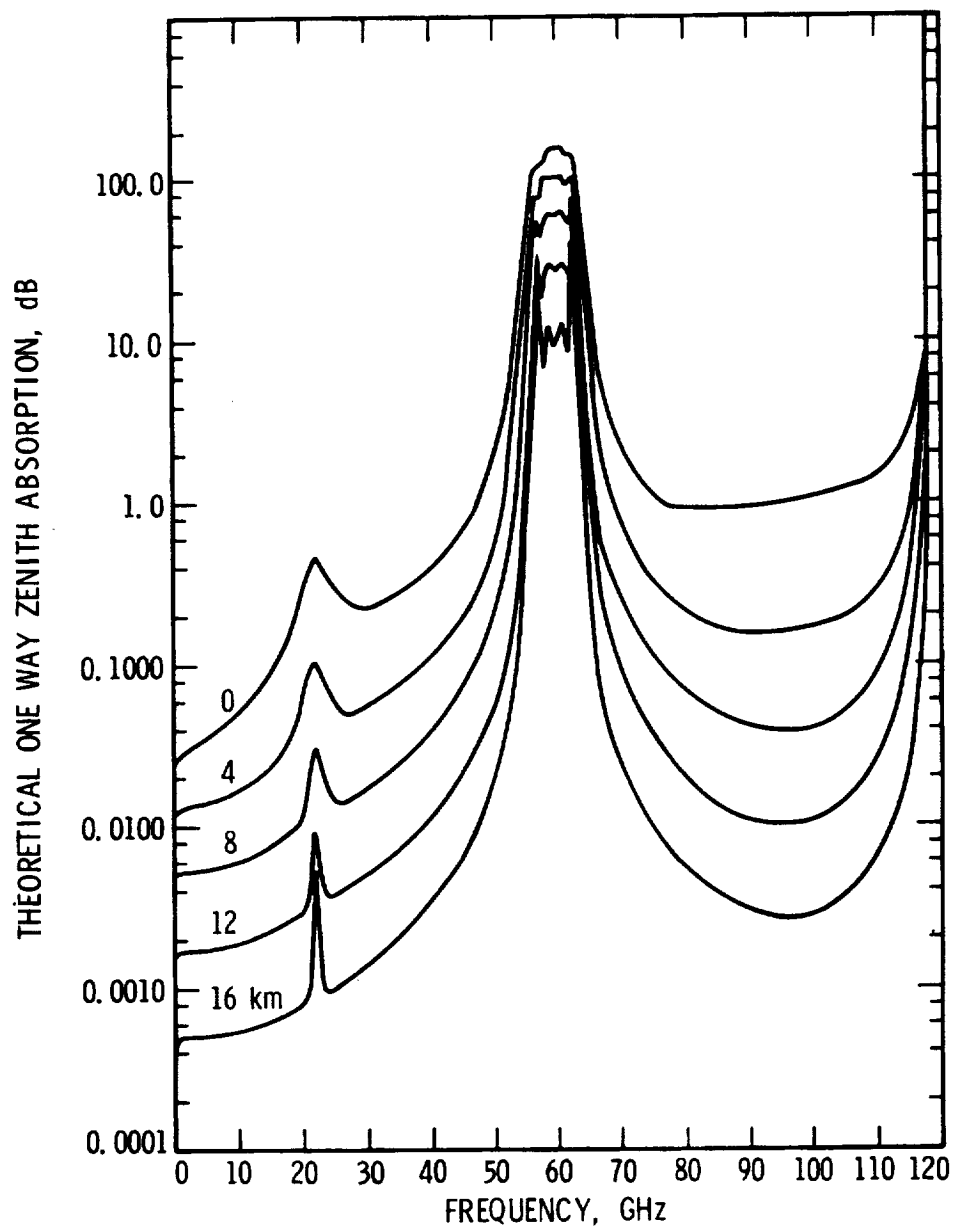


Figure 20. Zenith attenuation as a function of station elevation: 4-km height increments from 0 to 16 km. 7.5 g/m^3 water vapor at surface with 2-km scale height added to the 1976 U.S. standard model atmosphere (288 K at surface).

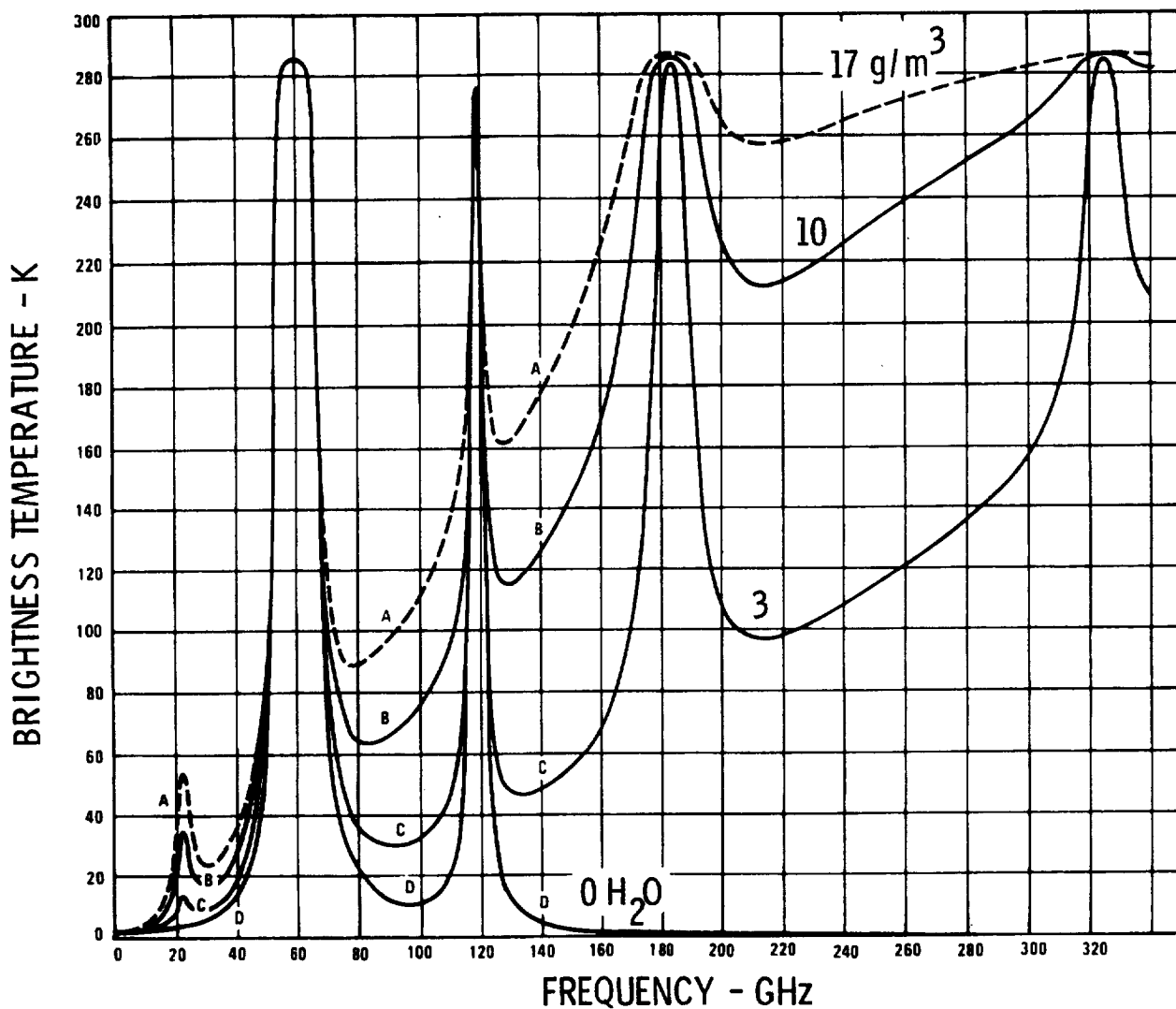


Figure 21. Zenith brightness temperature for 0, 3, 10, 17 g/m³ of water vapor (2-km scale height) added to the 1976 U.S. standard model atmosphere (surface temperature 288 K). 1 to 340 GHz. Note curve A is dashed because it is not physically realizable.

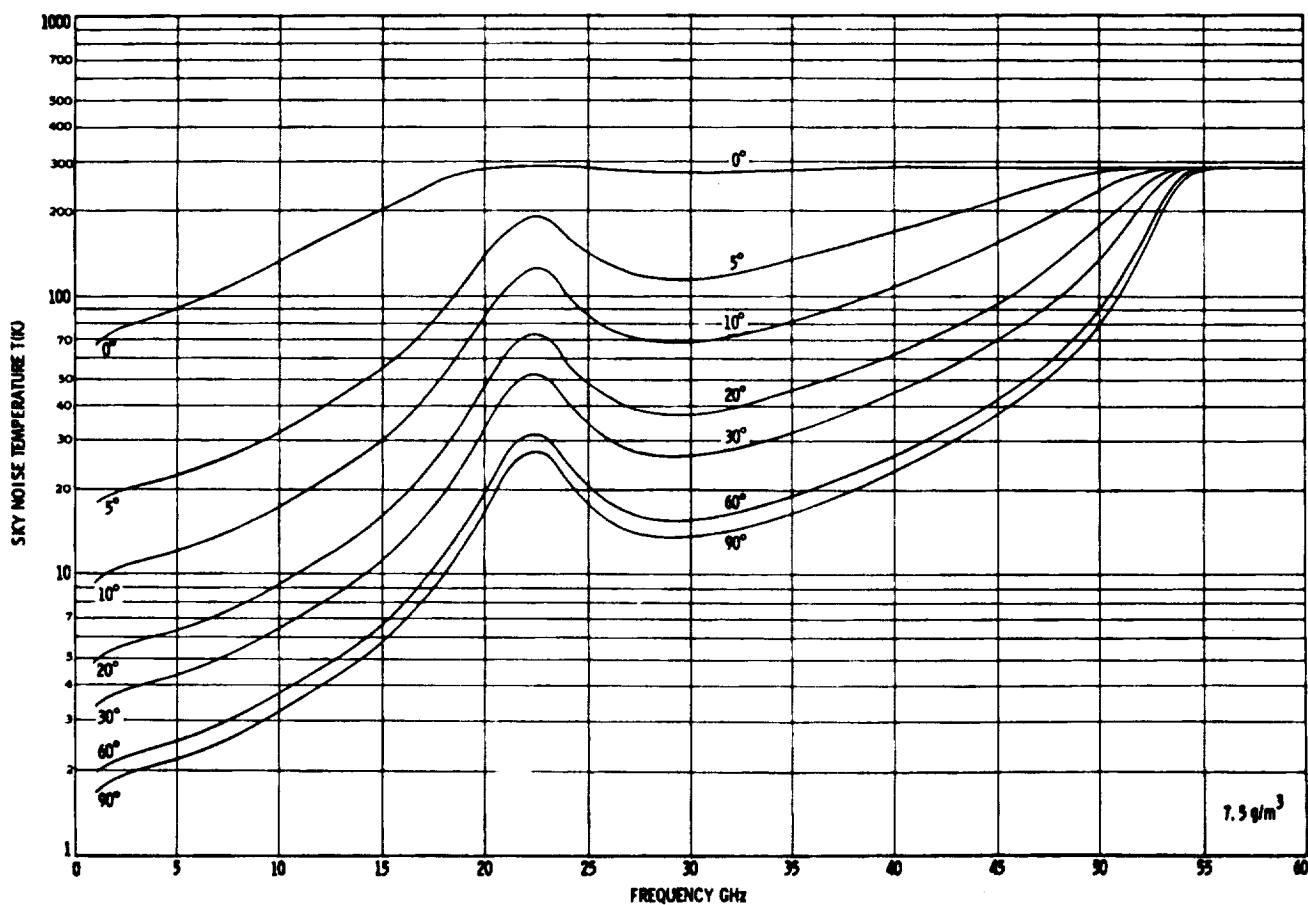


Figure 22. Brightness temperature for 7.5 g/m^3 water vapor (2-km scale height) added to the 1976 U.S. standard model atmosphere (surface temperature 288 K), 1 to 60 GHz.

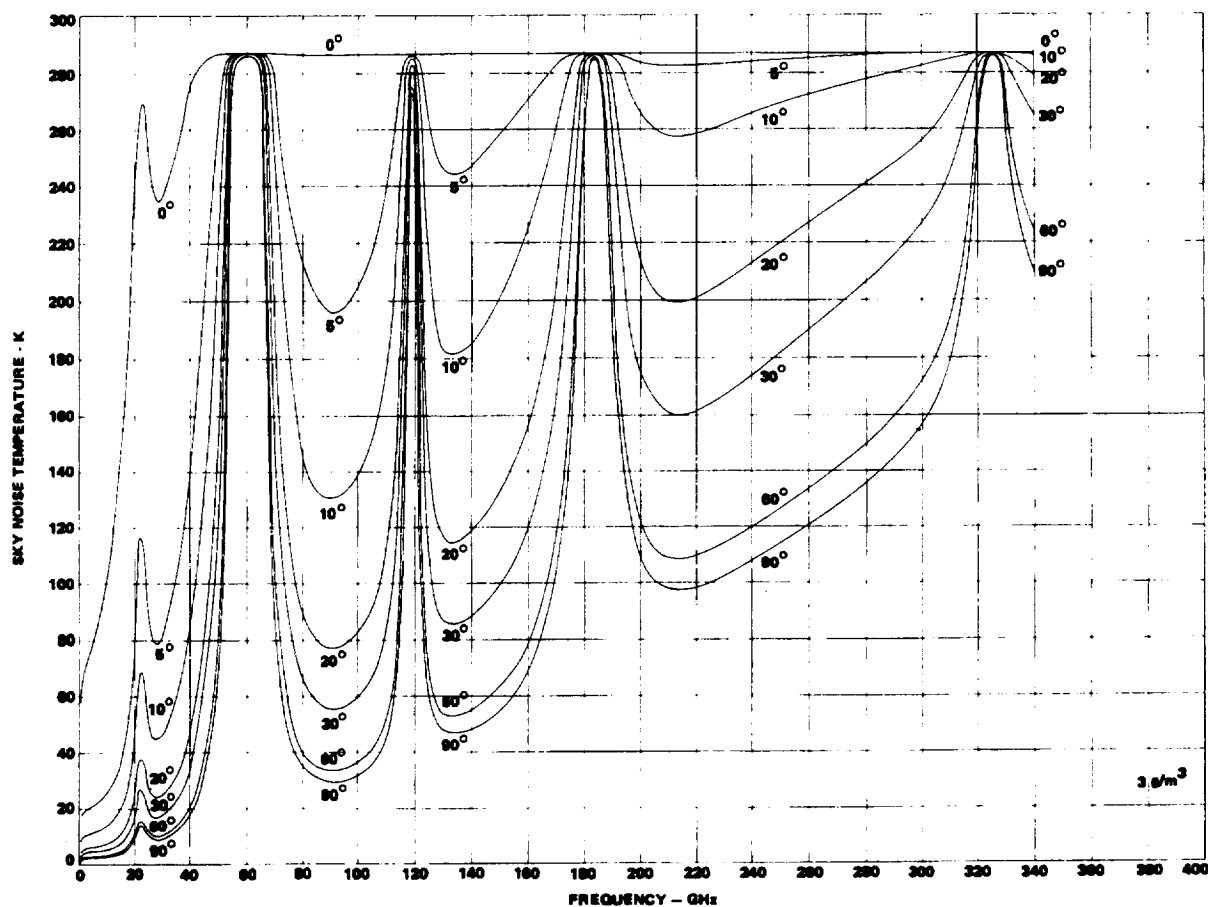


Figure 23. Brightness temperature for 3 g/m^3 water vapor (scale height 2 km) added to the 1976 U.S. standard model atmosphere, 1 to 340 GHz.

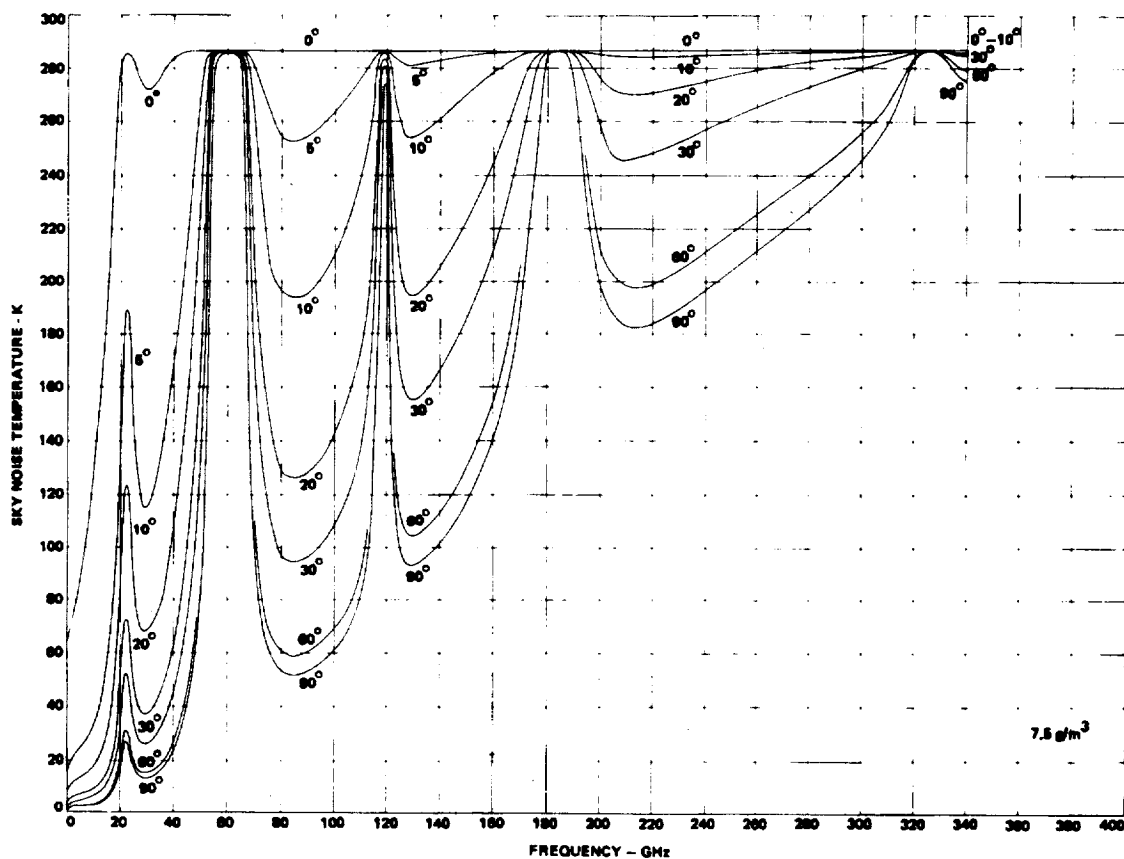


Figure 24. Brightness temperature for 7.5 g/m^3 water vapor (scale height 2 km) added to the 1976 U.S. standard model atmosphere, 1 to 340 GHz.

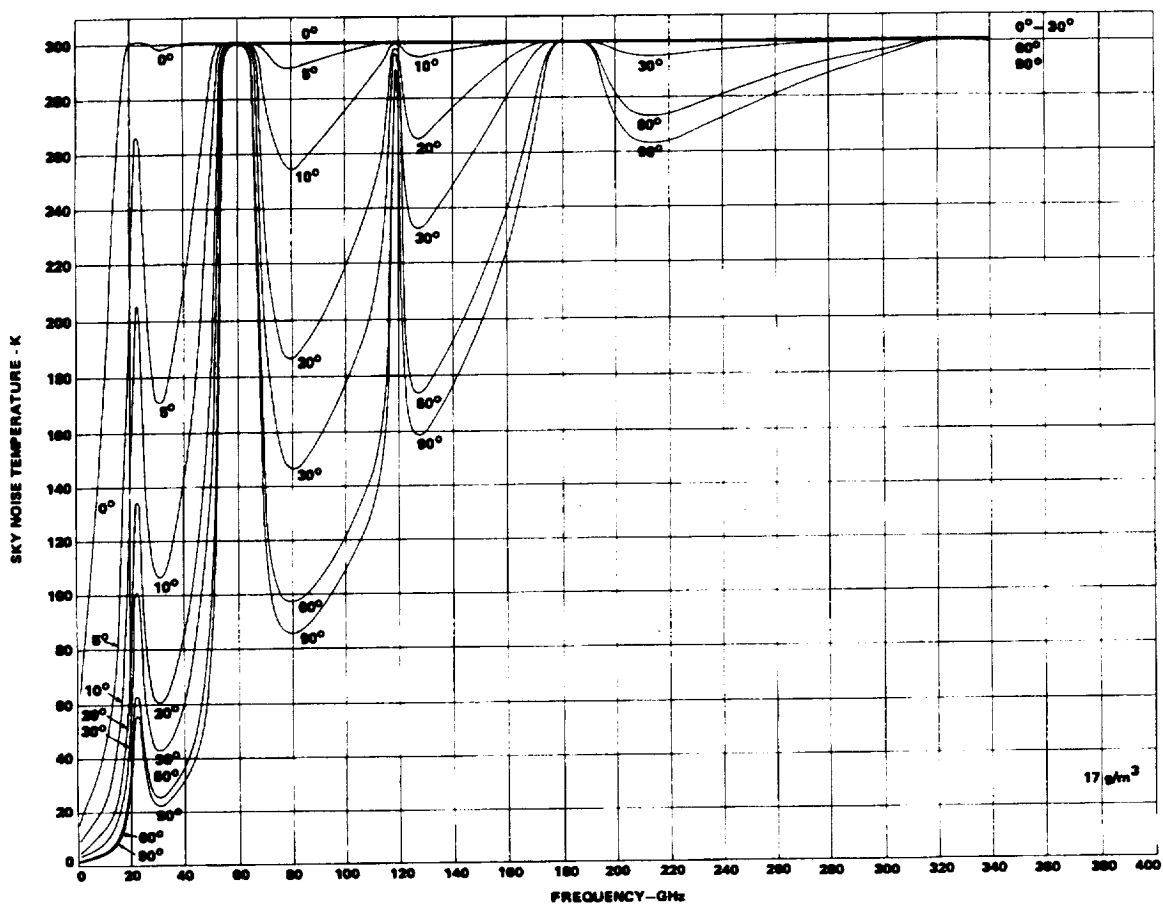


Figure 25. Brightness temperature for 17 g/m^3 water vapor (scale height 2 km) added to tropical model atmosphere (15°N) (Valley, 1965); 1 to 340 GHz.

